# Biosensing with Insect Odorant-Receptor Functionalised Carbon Nanotube Devices

## Introduction

So far in this thesis, multiple design schemes have been described for the construction of biosensors with insect odorant receptors. In **?@sec-fabrication**, transducers were fabricated and characterised which used either graphene or various carbon nanotube network morphologies for the conductive channel. These morphologies included highly bundled networks from dropcasting in an organic solution, and less bundled networks dropcast in surfactant solution either with or without steam present. Functionalisation approaches using the attachment linkers PBASE, PBA/EDC, pyrene-NTA and pyrene-biotin were discussed in **?@sec-noncovalent-functionalisation**, where linker functionalisation was investigated using electrical, spectroscopic and optical analysis techniques, including Raman spectroscopy and fluorescence microscopy. This investigation included a comparison of positive and negative aspects of each approach for their application in an iOR biosensor setting. The next step in the process was to integrate these components into a biosensor for testing in the redesigned vapour delivery system, as described in **?@sec-vapour-sensing-biosensors**. In the vapour delivery system, signal responses can be compared to those measured by the non-selective onboard reference sensors. However, it was important to first ensure the functionalised devices worked consistently as biosensors in the existing aqueous sensing setup, as described in **?@sec-pristine-characteristics**.

In the following chapter, aqueous sensing with insect odorant receptors was achieved with two different sensor functionalisation approaches, one where linker was attached to the transducer in organic solvent, and one where linker was preattached to odorant receptors and the process was performed entirely in aqueous solution. The first approach was more similar to those used previously for insect odorant receptor functionalisation ([Murugathas et al. 2019](#ref-Murugathas2019a), [2020](#ref-Murugathas2020)), but was not reproducible in a manner consistent enough for reliable testing with the vapour delivery system. A range of slight changes to this organic solvent functionalisation procedure were trialled to identify the source of the inconsistency in biosensor behaviour. The testing indicated that either surface coatings present on the device channels or the protective structure of the nanodiscs used were causing the quality of functionalisation to vary. The second approach, which eliminates both surface coatings and the nanodisc format, was therefore tested in the vapour delivery system. However, little response was shown by the functionalised sensor to the positive analyte. Finally, possible reasons for this lack of response are discussed.

## Aqueous Sensing of Ethyl Hexanoate with OR22a-functionalised Carbon Nanotube Transistor

### OR Nanodisc Functionalisation

A carbon nanotube network field-effect transistor device, fabricated using post-June 2023 methods as described in **?@sec-fabrication**, was functionalised with OR22a nanodiscs. The network used for the device was deposited using the steam-assisted surfactant method, and the device was encapsulated with AZ 1518 using the post-Jan 2023 photolithography mask. The functionalisation was performed as follows:

1. The device was exposed to UV light for 1 minute, placed in AZ 326 developer for 3 minutes, then rinsed with acetone, isopropanol and nitrogen dried.
2. The device was vacuum annealed for 1 hour at 150°C.

Note: Steps 1 & 2 were added to ensure any residual photoresist on the channel was removed or passivated before functionalisation, see **?@sec-photoresist-contamination**.

1. A solution of 1 mM PBASE (Setareh Biotech) in methanol was prepared by fully dissolving 2 mg PBASE in 5 mL methanol by vortex mixing at 1000 rpm in a dark room.

Note: PBASE was stored at -18°C for 18 months prior to use, and was thawed under vacuum for 15 minutes in dark conditions before opening.

1. The device was then rinsed with methanol, fully submerged in 1 mL of PBASE in methanol solution and left covered with parafilm for 1 hour, then rinsed with methanol for 15 s, rinsed with PBS for 15 s and nitrogen dried to remove residual PBASE.
2. The device was left dry and in darkness while collecting the OR22a nanodiscs from the -80°C freezer.
3. 10 µL OR22a nanodiscs (batch number ND-OR22a-SB018, 1.9 mg/mL, prepared 7 months earlier) were diluted in 1 mL freshly-prepared PBS.

Note: The full 1 mL was used to flush out the nanodisc vial when preparing the nanodisc solution, with successive additions and subtractions of 50 µL PBS into and from the vial.

1. The device was submerged in the OR22a nanodisc solution and left covered with parafilm for 1 hour, then rinsed with PBS for 15 s and gently nitrogen dried.

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| |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | |  |  |  |  |  |  |  |  |   Figure 1.1: Liquid-gated carbon nanotube network device transfer characteristics before and after OR22a nanodisc functionalisation. Source-drain voltage was = 100 mV for both the forward and reverse sweep. In (a), the characteristics are shown on a logarithmic scale, where the gate current for each transfer curve is shown with a dashed line. In (b), the characteristics are shown on a linear scale alongside a dashed line tangent to the subthreshold slope of the characteristic curve. The threshold voltage corresponding to the intercept of this slope with the x-axis is shown for each transfer characteristic curve. |

The liquid-gated electrical characteristics shown in [Figure 1.1](#fig-OR22a-TX-comparison) were taken using the B1500A semiconductor device analyser of the sensing channel (channel 7) before and after functionalisation with OR22a nanodiscs. The liquid-gate buffer used was PBS containing 0.5% v/v DMSO. The device exhibited ambipolar characteristics before functionalisation, which is typically seen for steam-deposited carbon nanotube films (**?@sec-electrical-characterisation-CNT**; **?@sec-cnt-devices**). However, -type behaviour dominates after device functionalisation due to a significant drop in -type conductance. A slight increase in hysteresis was observed post-functionalisation. Leakage current (shown by the dashed traces) never exceeded V, both before and after functionalisation. The significant change in electrical characteristics could be due to five possible factors adsorption of solvent onto the network, network attachment of PBASE without subsequent protein attachment, non-specific adsorption of protein onto the network, PBASE-mediated attachment of the membrane scaffold protein (MSP) of nanodiscs to the network, and PBASE-mediated attachment of odorant receptors to the network. As the nanodisc volume is much larger than that of the odorant receptor, any direct protein adsorption most likely adsorption of the nanodisc membrane onto the carbon nanotube network. Odorant receptor attachment with PBASE is therefore the only desirable functionalisation result for sensing purposes. Functionalisation of the channel resulted in a negative shift in threshold voltage of V. This significantly exceeds the threshold voltage shifts measured for both methanol adsorption ( V) and device exposure to PBASE in methanol ( V), confirming that protein has attached to the carbon nanotubes. However, both direct protein adsorption ([Bradley et al. 2004](#ref-Bradley2004); [Heller et al. 2008](#ref-Heller2008); [Kauffman and Star 2008](#ref-Kauffman2008)) and empty nanodisc membrane attachment ([Murugathas et al. 2019](#ref-Murugathas2019a)) should also lead to a significant negative threshold voltage shift and therefore increased -conduction in the liquid-gated transfer characteristic curve. In all three cases, the voltage shift is predominantly the result of negative charge transfer from the adsorbed proteins to the semiconducting carbon nanotubes ([Bradley et al. 2004](#ref-Bradley2004); [Heller et al. 2008](#ref-Heller2008); [Murugathas et al. 2019](#ref-Murugathas2019a)). It is likely that the negative shift observed results from some combination of the three types of attachment. It should be noted that while the size of the functionalisation-induced threshold voltage shift can be used to determine whether an amine-tagged protein has attached to the nanodisc network, it cannot be used to specifically determine whether odorant receptors have attached to the network.

Atomic force microscope images were taken of the device channels both before functionalisation and after sensing with the functionalised device to confirm the presence of nanodiscs. As far as the author knows, these are the first atomic force microscope images taken of iOR nanodiscs found on a sensing channel rather than on a separate carbon nanotube film; this was made possible by using the 20 µm wide aperture encapsulation mask discussed in **?@sec-encapsulation**. AFM images showing iOR-nanodisc functionalised carbon nanotube networks have been reported by Murugathas *et al.*, but these images were not of channels used for sensing ([Murugathas et al. 2019](#ref-Murugathas2019a)). These images are shown in [Figure 1.2](#fig-working-OR22a-AFM) (a) and (b). The visible features are much smaller than the agglomerated nanodisc features in the atomic microscope images taken by Murugathas *et al.* ([Murugathas et al. 2019](#ref-Murugathas2019a)). On the dense network morphology used here, the position of nanodisc clusters relative to the carbon nanotubes is also less distinct. To confirm whether nanodiscs have preferentially attached to the carbon nanotubes, a more quantitative approach is required.

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Since no trough-like artifacts are visible in either the pristine or functionalised atomic force microscope images in [Figure 1.2](#fig-working-OR22a-AFM) (a) and (b), a value of 1.8 nm was used as the mean substrate height for image processing. This height is shown against each carbon nanotube network using the Gwyddion software masking tool in [Figure 1.2](#fig-working-OR22a-AFM) (c) and (d). In Gwyddion, both images were then simplified to a binary representation, where features above a certain threshold were shown as white and features below shown as black. This representation, shown in [Figure 1.2](#fig-working-OR22a-AFM) (e) and (f), has the appearance of a cross-section through the network at the threshold height. The threshold was chosen as the minimum height where carbon nanotube spindles were no longer apparent in the functionalised image, 10 nm above the substrate. [Figure 1.2](#fig-working-OR22a-AFM) (e) shows only a few, sparsely distributed features, each measuring up to 50 nm across. These features may correspond to large nanotube-nanotube junctions, surfactant residue, or other surface contamination (**?@sec-pristine-morphology**). In [Figure 1.2](#fig-working-OR22a-AFM) (f), many features are over 50 nm across. They are often found close together, and form a curved line across the network in the bottom left corner (shown in red); this arrangement of nanodisc features is similar to that reported previously for OR22a nanodiscs on sparser, more bundled networks ([Murugathas et al. 2019](#ref-Murugathas2019a)).

[Figure 1.2](#fig-working-OR22a-AFM) (a) shows that the maximum image height of the OR nanodisc-functionalised channel is 26 nm, while [Figure 1.2](#fig-working-OR22a-AFM) (f) shows only nanodisc features are present at 12 nm. Therefore, nanodisc agglomerates at least 14 nm tall are present on the channel. Assuming a average carbon nanotube height of 1.45 nm, with an average substrate height of 1.8 nm, the nanodisc agglomerates visible in [Figure 1.2](#fig-working-OR22a-AFM) could be up to 23 nm tall. The estimated height range for nanodiscs is 10 20 nm ([Nath, Atkins, and Sligar 2007](#ref-Nath2007); [Bayburt and Sligar 2010](#ref-Bayburt2010); [Murugathas et al. 2020](#ref-Murugathas2020); [Cheema et al. 2021](#ref-Cheema2021)). It is possible that nanodiscs form a single layer on the carbon nanotube network. Height measurements of biological samples taken via AFM have been shown to underestimate actual feature height by over 50% ([Vobornik et al. 2023](#ref-Vobornik2023)). Even so, assuming this squishing effect is not significantly in excess of 50%, the agglomerates are only a few nanodiscs high at most. As the nanodisc agglomerates are up to 200 nm across at their widest point ([Figure 1.2](#fig-working-OR22a-AFM)), comprising of at least 20 nanodiscs, it appears that the clustering behaviour is primarily across the plane rather than vertical. It appears that, rather than nucleating in solution about a central point prior to attachment, the nanodiscs are individually attaching to preferred locations on the network.

This attachment behaviour can be contrasted with the behaviour observed in the atomic microscope image of agglomerated OR22a nanodiscs taken by Murugathas *et al.* ([Murugathas et al. 2019](#ref-Murugathas2019a)). The network is significantly sparser, so the relative extent of clustering at different points is easier to discern. There is clearly significant variation in nanodisc attachment across a single nanotube bundle, and it appears that clustering is more significant at junctions between carbon nanotube bundles. Preferred attachment locations away from junctions could result from the higher reactivity of exposed metallic CNTs ([Cao and Rogers 2009](#ref-Cao2009)), or from regions which are particularly clean of contamination. Interestingly, while the OR22a nanodisc features seen by Murugathas *et al.* via AFM are similar in breadth to those seen here, OR agglomerates which are at least 53 nm tall are present ([Murugathas et al. 2020](#ref-Murugathas2020)). It is unclear why the extent of vertical agglomeration differs between this work and that of Murugathas *et al.*, but may be linked to the difference in morphology between the networks used. One possibility is that nanodiscs will preferentially attach to metallic carbon nanotubes, but prefer to attach to each other instead of semiconducting nanotubes. A semiconducting tubes in a highly bundled network may block proteins from accessing metallic tubes in the same bundle, leading to a greater degree of self-attachment.

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Fluorescence microscopy was also used to confirm the presence of GFP-tagged odorant receptors on the carbon nanotube network. A device was functionalised using nanodiscs with odorant receptors attached to *Aequorea Victoria* green fluorescent protein (GFP) using the process described at the beginning of this section. When these nanodiscs were used, the functionalisation was performed in darkness, with the odorant receptor nanodisc vial transported under an opaque cover to protect it from light (batch number ND-GFP-OR43b-0002, prepared 12 months earlier). After functionalisation, devices were briefly rinsed with DI water and nitrogen dried to remove dried-down salt residue left by the PBS. A control device was also prepared without the use of PBASE, skipping steps 3 and 4 in the functionalisation process. Fluorescence images of the GFP-OR functionalised and control devices are shown in [Figure 1.3](#fig-PBASE-GFP-ORs). Note that fluorescence microscope images were taken immediately after functionalisation; devices were transported to the fluorescence microscope room in a foil-wrapped container, and the fluorescence microscope room was kept dark while images were taken.

The silicon dioxide regions in each image appear bright under the GFP filter, indicating attachment between the GFP-OR nanodiscs and the silicon dioxide substrate has occurred. As this device has been annealed, UV exposed and developed before functionalisation, the likelihood this unwanted attachment is to residual photoresist is reduced significantly (see **?@sec-photoresist-contamination**). The SiO substrate also appears brighter in the images on the right of [Figure 1.3](#fig-PBASE-GFP-ORs), which are of the device initially exposed to PBASE. The discussion in **?@sec-pyrene-interactions** indicates that the pyrene moiety of PBASE interacts with the silicon dioxide substrate. Assuming no significant variation in the fluorescence of GFP between nanodisc vials, the PBASE coating appears have led to more nanodiscs attaching to the silicon dioxide, giving rise to the brighter fluorescence of the silicon dioxide seen for the PBASE-incubated device on the right of [Figure 1.3](#fig-PBASE-GFP-ORs).

A comparison of fluorescence in the channel region between images on the left of [Figure 1.3](#fig-PBASE-GFP-ORs) (GFP-OR nanodiscs) and the images on the right (GFP-OR nanodiscs and PBASE) is given by the inset in [Figure 1.3](#fig-PBASE-GFP-ORs) (c)-(f). The inset demonstrates that the channels not incubated in PBASE are significantly less bright than those that had been incubated with PBASE. It appears that the presence of GFP-OR nanodiscs in PBS is limited on these channels. However, when the carbon nanotubes are modified with PBASE, the GFP-OR nanodiscs are able to attach to the channel, and so the channel shows up brightly under the fluorescence microscope GFP filter. Importantly, since the GFP is attached to odorant receptors rather than the nanodiscs themselves, there must be odorant receptors present on the channel after functionalisation; attachment to the channel is not limited to empty nanodiscs. This trend was consistent across all conducting channels on each of the two devices. As far as I know, this is the first time fluorescence has been used to investigate the attachment of odorant receptor nanodiscs to a carbon nanotube network.

### Aqueous Sensing of Ethyl Hexanoate

The procedure used for biosensor detection of ethyl hexanoate in liquid was the same as the procedure outlined in **?@sec-dummy-sensing**, except 0.5% v/v DMSO was present in the buffer solution (to improve ethyl hexanoate solubility) and dilutions of ethyl hexanoate in the same 0.5% v/v DMSO PBS buffer solution were added during the sensing series. Dilutions of 1 fM, 1 pM, 1 nM and 1 µM ethyl hexanoate in 0.5% v/v DMSO PBS were prepared before device characterisation according to [Table 1.1](#tbl-dilution-preparation), using pre-prepared concentrations of 200 fM, 200 pM, 200 nM and 200 µM ethyl hexanoate in DMSO. The ethyl hexanoate in DMSO dilutions were prepared beforehand as a 1:10 dilution series in DMSO using 200 mM stock solution, where dilutions ranged from 20 mM to 200 fM. Sampling measurements were taken using the B1500A semiconductor device analyser, with the transfer measurement in [Figure 1.1](#fig-OR22a-TX-comparison) (b) taken directly before sensing. The full control series plus sensing sequence is shown in [Figure 1.4](#fig-EtHex-aqueous-sensing). Gate current remained negligible across the entire sensing procedure.

Table 1.1: Preparation of analyte dilutions in 1XPBS from solutions of analyte in DMSO. The 1XPBS used was prepared on the same day as the dilution process.

| Conc. in DMSO | 1XPBS added | Final volume | Final conc. |
| --- | --- | --- | --- |
| 5 µL × 0 fM | 995 µL | 1 mL | 0 fM, 0.5% v/v DMSO |
| 5 µL × 200 fM | 995 µL | 1 mL | 1 fM, 0.5% v/v DMSO |
| 5 µL × 200 pM | 995 µL | 1 mL | 1 pM, 0.5% v/v DMSO |
| 5 µL × 200 nM | 995 µL | 1 mL | 1 nM, 0.5% v/v DMSO |
| 5 µL × 200 µM | 995 µL | 1 mL | 1 µM, 0.5% v/v DMSO |

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| Figure 1.4: The control series ( s) and ethyl hexanoate sensing series () of the OR22a-functionalised device channel. Source-drain voltage was set at = 100 mV while gate voltage was set at = 0 V. Functionalisation and sensing was performed using the methods developed in this thesis by Danica Fontein, School of Chemical and Physical Sciences, Te Herenga Waka - Victoria University of Wellington. |

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The control series for the sensing series is shown in [Figure 1.5](#fig-OR22a-series) (a). No clear stepwise response is seen to buffer additions or subtractions. The functionalised device shows similar baseline drift behaviour to that of a pristine device, with a period of short-term decay quickly yielding to a more long-lived decay behaviour. A linear fit to the region s had a gradient of pA/s. This gradient is smaller than the range of values found for the linear fit approximating the longer-term drift of a pristine device (**?@sec-baseline-drift**), but of the same order of magnitude. The linear fit was then subtracted from the control series and an exponential fit was performed on the remaining dataset, as shown in [Figure 1.5](#fig-OR22a-series) (b). A value of s was found for the exponential time constant, similar to those found for the channels of the pristine device. This confirms that the 1800 s control series is sufficient to avoid the presence of short-term decay during sensing.

It appears that the exponential fit overestimates current measurements between 1100 s and 1500 s and underestimates measurements between 1500 s and 1800 s. This deviation from the fit may result from the linear approximation used to represent long-term baseline drift being weaker for this channel than for those discussed previously in **?@sec-dummy-sensing** and **?@sec-pristine-EtHex**. This could result from the exponential terms for long-term baseline drift having relatively short time constants, so no longer holds and higher order terms in the linear approximation are no longer negligible. This observation may indicate a relationship exists between device functionalisation and the long-lived device decay behaviour. However, it may simply result from the natural variation between randomly-deposited device channels. Further work may be required to confirm the existence of such a relationship, though this work is outside the scope of this thesis.

[Figure 1.5](#fig-OR22a-series) (c) shows the cleaned and filtered ethyl hexanoate sensing data from the OR22a-functionalised device from 1800 s onwards. The concentration of each 20 µL addition is indicated above the corresponding addition time. The actual concentration in the liquid-gate well is determined by both the concentration of analyte being added and the volume of 1XPBS 0.5% v/v DMSO already present. The concentration of ethyl hexanoate in the well after each addition is shown in [Table 1.2](#tbl-concentrations). With each addition of ethyl hexanoate, a subsequent rapid drop in source-drain current across the channel was observed. This current decrease appears irreversible, as the current stabilises after each addition at a lower current level than prior to the addition. The relationship between ethyl hexanoate concentration in the sensing well and the first four signal responses of the OR22a-functionalised device are shown in [Figure 1.6](#fig-EtHex-responses). Both mammalian and insect odorant receptors show a logarthmic electrical response to low concentrations of target analyte, while responses saturate at higher analyte concentrations ([Persaud and Dodd 1982](#ref-Persaud1982); [Khadka et al. 2019](#ref-Khadka2019); [Murugathas et al. 2020](#ref-Murugathas2020); [Cheema et al. 2021](#ref-Cheema2021)). This trend has been observed for OR22a responses to both methyl hexanoate and ethyl hexanoate on different sensing platforms, where saturation occurs at high picomolar concentrations. As in previous works, all responses were observed without requiring an ORCO coreceptor present ([Murugathas et al. 2019](#ref-Murugathas2019a), [2020](#ref-Murugathas2020); [Khadka et al. 2019](#ref-Khadka2019); [Cheema et al. 2021](#ref-Cheema2021)).

Table 1.2: Comparison of ethyl hexanoate analyte in the 20 µL additions to the total ethyl hexanoate concentration in the liquid-gate electrolyte, alongside the volume of electrolyte in the PDMS well after each addition.

| Addition # | 1 | 2 | 3 | 4 | 5 | 6 |
| --- | --- | --- | --- | --- | --- | --- |
| Addition conc. | 0 fM | 1 fM | 1 pM | 1 nM | 1 µM | 1 µM |
| Volume in well | 100 µL | 120 µL | 140 µL | 160 µL | 180 µL | 200 µL |
| Conc. in well | 0 fM | 170 aM | 140 fM | 130 pM | 110 nM | 200 nM |

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| Figure 1.6: Device response against the ethyl hexanoate (EtHex) concentration present in the device liquid-gate corresponding to the first four 20 µL analyte additions. |

However, the final addition resulted in an unexpectedly large response of 45% which dramatically deviates from this well-established trend. This large response occurs when the concentration of ethyl hexanoate in the well is roughly doubled from 100 nM to 200 nM. The size of this response well exceeds any error due to insufficient mixing in the PDMS, which is usually on the scale of 1% (**?@sec-salt-conc-series**). The analsyis in the subsequent section ([Section 1.3](#sec-variability)) demonstrates that this response cannot be explained as the carbon nanotubes (or nanodiscs) responding to a relatively large concentration of ethyl hexanoate directly. No significant changes in gate current occur during the sensing series ([Figure 1.4](#fig-EtHex-aqueous-sensing)), so the response cannot be explained as being due to changes in the gate capacitance due to leakage current. The responses of OR22a to target analyte at liquid-gate concentrations above 1 nM have not previously been investigated for field-effect transistor sensors ([Murugathas et al. 2019](#ref-Murugathas2019a), [2020](#ref-Murugathas2020)). More research may be required to understand device behaviour at analyte concentrations well above the apparent saturation regime at high picomolar concentrations.

## Addressing Biosensor Variability

### Variability in Biosensor Behaviour

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| Figure 1.7: The normalised sensing series of another OR22a-functionalised device across six multiplexed channels, where current data has been despiked, baseline drift removed and a moving median filter applied. The concentration of each 20 µL addition is indicated above the time of addition. |

Despite the successful detection of ethyl hexanoate by an OR22a nanodisc-functionalised biosensor in [Section 1.2](#sec-aqueous-sensing-EtHex), it was found that this behaviour was not readily reproducible. The results from the previous section were not repeated when using the same procedure for fabrication of devices alongside an identical functionalisation process with the same batch of OR22a nanodiscs (ND-OR22a-SB018). The ethyl hexanoate sensing sequence from six functionalised device channels is shown in [Figure 1.7](#fig-OR22a-variability). The current response to each analyte addition is similar to that seen after the initial addition without ethyl hexanoate present. The largest contributing factor to current change appears to be drift. Unlike the clear decreases in current subsequent to ethyl hexanoate additions seen in [Figure 1.5](#fig-OR22a-series) (c), no decreases are seen in [Figure 1.7](#fig-OR22a-variability) to any ethyl hexanoate solution addition. It is clear that although the same process has been followed here as in [Section 1.2.2](#sec-EtHex-aqueous-sensing), the functionalised device is not responding to the presence of target analyte. The device characteristics were therefore investigated for differences from the functionalisation results seen in [Section 1.2.1](#sec-working-PBASE-functionalisation).

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Liquid-gated electrical characteristics were taken of each sensing channel from this device before and after functionalisation with OR22a nanodiscs, in the same manner as in [Section 1.2.1](#sec-working-PBASE-functionalisation). These characteristics are shown in [Figure 1.8](#fig-OR22a-variability-TX). The average threshold shift was , the same as that of a device functionalised with PBASE in methanol without subsequent functionalisation with OR22a nanodiscs. To test whether protein was present on the channel, an atomic force microscope image was taken of channel 6. The resulting image is shown in [Figure 1.9](#fig-OR22a-variability-AFM-comparison) (a) with the mean substrate height (1.8 nm) masked in green. A binary representation of the image was also prepared with a 11.8 nm threshold, shown in [Figure 1.9](#fig-OR22a-variability-AFM-comparison) (b). As in [Figure 1.2](#fig-working-OR22a-AFM) (f), the surface is densely populated with non-nanotube features over 50 nm across. These features also form clusters and curvilinear patterns across the network. Nanodisc agglomerates 28 37 nm in height are therefore present on channel 6 ([Section 1.2.1](#sec-working-PBASE-functionalisation)), despite the lack of a significant threshold shift subsequent to functionalisation. The agglomerates are still relatively small compared to those reported by Murugathas *et al.*, so the large size of nanodiscs in [Figure 1.9](#fig-OR22a-variability-AFM-comparison) relative to those in [Section 1.2.1](#sec-working-PBASE-functionalisation) is unlikely to be an issue ([Murugathas et al. 2019](#ref-Murugathas2019a)).

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| Figure 1.10: Real-time sampling using channel 4 of the device modified with OR22a nanodisc solution without prior exposure to PBASE or methanol. A 20 µL addition of 1% v/v DMSO PBS was made at 200 s. Subsequently, 20 µL additions of ethyl hexanoate diluted in 1% v/v DMSO PBS were made at 400 s, 600 s, 800 s and 1000 s and 1200 s, with the concentration of each addition indicated above the time of addition. |

Both OR nanodisc and empty nanodisc attachment via PBASE have been shown to cause significant gating of the network ([Section 1.2.1](#sec-working-PBASE-functionalisation)). The amine group on proteins can be attached directly onto carbon nanotubes by adsorption, although this attachment is relatively weak ([Bradley et al. 2004](#ref-Bradley2004)). [Figure 1.9](#fig-OR22a-variability-AFM-comparison) (c) shows an AFM image of a carbon nanotube network film after submersion in a 10 µL/mL OR22a nanodisc in PBS solution for 1 hour (batch NDOR22a-0016-1), without prior exposure to PBASE in methanol. A 1.1 nm image artifact (see **?@sec-pristine-AFM**) is present in the lower left of the image, circled in grey, and so the average substrate height of the image is 2.9 nm, highlighted green in [Figure 1.9](#fig-OR22a-variability-AFM-comparison) (c). A binary representation of this AFM at with a threshold height of 12.9 nm is shown in [Figure 1.9](#fig-OR22a-variability-AFM-comparison) (d), where nanodisc agglomerations are clearly visible. Therefore, it might be reasoned that the lack of a gating effect, but with nanodiscs present, results from a direct attachment mechanism which circumvents the PBASE linker.

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| Figure 1.11: Liquid-gated carbon nanotube network device transfer characteristics from channel 4 of a device placed in OR22a nanodisc solution for 1 hour, without prior exposure to PBASE or methanol, before and after functionalisation. Source-drain voltage was = 100 mV. |

[Figure 1.10](#fig-OR22a-variability-noPBASE-sensing) shows the sensing results from the device functionalised without the use of PBASE. Small, positive current responses to additions of ethyl hexanoate diluted in 1% v/v DMSO PBS are visible. These responses may may result from the weakly attached OR22a nanodiscs being mechanically removed by the pressure of each addition on the device channels. While the sensing response is vaguely similar to that seen in [Figure 1.7](#fig-OR22a-variability), the electrical characteristics of the device channel are starkly different to those in [Figure 1.8](#fig-OR22a-variability-TX). These channel characteristics are shown in [Figure 1.11](#fig-OR22a-variability-TX-comparison). The negative threshold shift was -0.27 V, far larger than any seen in [Figure 1.8](#fig-OR22a-variability-TX) and similar in size to the threshold shift after functionalisation seen for the working biosensor in [Figure 1.1](#fig-OR22a-TX-comparison). Despite the difference in attachment mechanism, there is still significant electrical modification of the channel by the nanodiscs not seen for the unresponsive device in [Figure 1.7](#fig-OR22a-variability). It appears that attachment by mechanisms other than PBASE cannot sufficiently explain the variability in sensor behaviour.

A new explanation is therefore required for this apparently contradictory scenario where nanodiscs can be present on a device channel without significant gating effects. The most straightforward explanation is that no reliable correlation exists between the two phenomena. Given the consistent threshold shift results for various linker functionalisations seen in **?@sec-noncovalent-functionalisation**, this scenario implies a significant variation in protein structure and charge behaviour within a single nanodisc batch, which seems unlikely. Another possibility is that some type of surface coating is causing nanodiscs to not attach to either PBASE or the carbon nanotubes. This surface coating might be attractive, attaching to both nanodiscs and carbon nanotubes, but forming a barrier layer between the two. Alternatively, this coating might be repulsive, causing nanodiscs to attach weakly to the substrate around the carbon nanotubes and not the nanotubes themselves. Variations in the degree to which a network is coated may then explain why the same functionalisation method might work for one device but not another. The following section investigates ways of eliminating possible sources of surface coating for more reliable functionalisation results.

### Potential Sources of Variability

Throughout the course of this thesis, multiple potential candidates for the unwanted surface coating discussed in the previous section have been identified. These include the surfactant used in carbon nanotube deposition (**?@sec-pristine-morphology**, **?@sec-pristine-electrical-characterisation**), the solvent used in functionalisation (**?@sec-PBASE-electrical-characterisation**), residual photoresist (**?@sec-photoresist-contamination**), and the hydrophobic layer which naturally forms on graphene and carbon nanotubes in air (**?@sec-hydrophobicity**). Another possibility is that PBASE itself is acting as a surface coating, which could result from multilayer coverage restricting access by the odorant receptors to directly attached PBASE (**?@sec-PBASE-attachment**). Alternatively, PBASE may have hydrolysed into PBA prior to attachment, forming an inert surface layer upon -stacking around the carbon nanotubes. However, no threshold shift directly attributable to PBA attachment should occur (**?@sec-PBA-characterisation**), and this is not what was observed when characterising the non-working device in [Section 1.3.1](#sec-variability-biosensor). To understand which of these candidates is responsible for the significant variability in biosensor functionality, the sensing procedure was performed with slight variations on the biosensor fabrication and functionalisation procedures. In each test, an individual element of one of these procedures was altered to prevent the introduction of a specific surface coating. The biosensor was then characterised and tested to see if it would respond to its target odorant.

#### Spurious Responses

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| Figure 1.12: Response to changing the concentration of DMSO in the PDMS well of a OR22a-functionalised sensor. Source-drain voltage was set at = 100 mV while gate voltage was set at = 0 V. The well originally contained 100 µL of 1% v/v DMSO 1X PBS. 20 µL additions of DMSO in PBS were made at 3300 s and 3600 s. |

Before testing to see if a surface coating was responsible for the lack of response seen to ethyl hexanoate by the device in [Section 1.3.1](#sec-variability-biosensor), it was important to investigate the possibility the signals seen in [Section 1.2.2](#sec-EtHex-aqueous-sensing) were false positives. The highly sensitive device channel could credibly respond to three different rapid environmental changes occurring with each addition: the mechanical action of the addition, a difference between the 0.5% v/v DMSO in PBS containing the analyte and the 0.5% v/v DMSO in PBS already in the well, or a direct response to analyte. It is important to eliminate the first two possibilities to be certain that the device is responding to analyte. The control series as it stands demonstrates responses cannot be explained by mechanical action. All analyte solutions are prepared simultaneously using the same PBS, taking care to avoid cross-contamination, so responses are unlikely to result from a difference between the PBS in the analyte solution and the PBS in the well. It then must be verified whether a functionalised device channel will respond to a change in DMSO concentration, which is the result of the DMSO concentration in an analyte addition being different to the concentration in the PDMS well.

[Figure 1.12](#fig-DMSO-concentration) shows that a increase in DMSO concentration in the well from 1% v/v to 2.5% v/v leads to a steep drop in current of 0.5% 1.5% across two OR22a-functionalised device channels, significantly smaller than the >2% changes seen in [Section 1.2.2](#sec-EtHex-aqueous-sensing). Furthermore, precision of the measurements used for analyte preparation means that a change in proportion of DMSO in the well of this scale during a sensing sequence is unlikely. It therefore seems improbable that a change in DMSO concentration is causing the sensing responses in [Section 1.2.2](#sec-EtHex-aqueous-sensing). However, the author recommends a slight modification to the control series used earlier for a more robust experimental baseline in future works. For a device with 100 µL 0.5% v/v DMSO PBS in the well after the first buffer addition at 100 s, a subsequent 20 µL addition of 1% v/v DMSO PBS at 200 s and 20 µL addition of 0% v/v DMSO PBS addition at 300 s can be used to check for spurious responses due to changing DMSO concentration, while ensuring the DMSO concentration in the well is 0.5% v/v after the control series.

#### Fabrication

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| Figure 1.13: The normalised sensing series of the solvent-deposited, OR22a-functionalised device across six multiplexed channels, = 100 mV and = 0 V, where current data has been despiked, baseline drift removed and a moving median filter applied. |

Two different approaches were trialled to eliminate possible surfactant contamination, both of which drew heavily on previous methods used for iOR biosensor fabrication ([Murugathas et al. 2019](#ref-Murugathas2019a), [2020](#ref-Murugathas2020)). Solvent-deposited carbon nanotube network and graphene devices were fabricated as described in **?@sec-qw-processing**. The same functionalisation process for each device was used as described in [Section 1.2.1](#sec-working-PBASE-functionalisation) with OR22a nanodiscs.

The normalised sensing behaviour for the solvent-deposited carbon nanotube device is shown in [Figure 1.13](#fig-solvent-deposited-sensing). Gate current remained negligible across this time period (<0.1% of average drain current). No current change subsequent to each addition exceeded 2%, and current changes appear negligible on the scale of the changes seen in [Section 1.2.2](#sec-EtHex-aqueous-sensing). Deviations from linear drift dominate the change in current across the sensing run, especially for channels 2 and 3. [Figure 1.15](#fig-solvent-deposited-sensing-TX) shows that the average threshold shift from functionalisation was V, which indicates attachment of PBASE but not nanodiscs. As the pre-2023 encapsulation mask was used, an AFM was taken of a separate film modified in the same manner before and after functionalisation [Figure 1.16](#fig-solvent-deposited-AFM-comparison) (a) and (b) respectively. Attached nanodisc aggregations are clearly visible. Rather than appearing similar to the atomic force microscope images of an OR22a-functionalised highly-bundled morphology in the literature, the functionalised film image appears closer in nature to those observed for the OR35a-functionalised and empty nanodisc functionalised highly-bundled film ([Murugathas et al. 2019](#ref-Murugathas2019a)). [Figure 1.16](#fig-solvent-deposited-AFM-comparison) (c) and (d) show that over a larger scale these aggregations can be over 300 nm tall, forming large galaxy-like clusters which indicate mutual interaction during deposition. These results lend further support to the relationship between network morphology and vertical aggregation of nanodiscs, as discussed in [Section 1.2.1](#sec-working-PBASE-functionalisation).

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The electrical characteristics of a graphene device channel before and after functionalisation with OR22a nanodiscs in the manner outlined previously are shown in [Figure 1.14](#fig-graphene-sensing-TX) (a), showing an order of magnitude decrease in on-current and a negatively shifted Dirac point with functionalisation, as seen previously for working OR22a nanodisc GFET biosensors ([Murugathas et al. 2020](#ref-Murugathas2020)). [Figure 1.14](#fig-graphene-sensing-TX) (b) shows when the process is repeated on another device without initial exposure to PBASE and methanol, a larger negative shift in the Dirac point is observed. It appears the initial functionalisation with PBASE and methanol decreases the charge transferred to the graphene when the nanodiscs are introduced; the difference between these two surface modifications is analogous to that seen for the carbon nanotube devices in [Section 1.3.1](#sec-variability-biosensor). A pristine graphene surface and a OR22a-functionalised graphene surface are shown in [Figure 1.16](#fig-solvent-deposited-AFM-comparison) (e) and (f) respectively. Graphene folds of up to 7.3 nm in height are visible on the right hand side of [Figure 1.16](#fig-solvent-deposited-AFM-comparison) (a). When functionalised with OR22a nanodiscs, the surface is densely coated with nanodisc aggregates up to 250 nm across and 30 nm tall. These nanodiscs are a similar height and size to those observed by Murugathas *et al.* ([Murugathas et al. 2020](#ref-Murugathas2020)).

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| Figure 1.17: A normalised ethyl hexanoate sensing series taken with a OR22a-functionalised graphene device. Source-drain voltage was set at = 100 mV while gate voltage was set at = 0 V. The concentration of each 20 µL addition is indicated above the time of addition, with additions made at 500 s, 1000 s, 1500 s, 2000 s and 2500 s. |

Both the transfer characteristics and atomic force microscope image indicates widespread attachment of nanodiscs. However, the normalised current data from a OR22a nanodisc graphene field-effect transistor in [Figure 1.17](#fig-graphene-sensing) shows current changes of <1% in response to ethyl hexanoate additions. This contrasts with the OR22a nanodisc-functionalised graphene device behaviour observed by Murugathas *et al.*, where target analyte additions with concentration above 10 fM consistently caused current changes of above 2% ([Murugathas et al. 2020](#ref-Murugathas2020)). Again, there appears to be an unresolved functionalisation issue that is not clearly captured either by the atomic force microscope images or the transfer characteristics before and after functionalisation of the graphene devices. It appears that avoiding the use of surfactant on the transducer element is not sufficient to ensure consistent iOR biosensor functionalisation; it therefore seems likely that a surfactant coating is not the primary reason for the observed variability in device operation. Furthermore, the confound appears to persist across multiple transducer morphologies which show significant variations in both their active surface area and electrical properties.

#### Functionalisation

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| Figure 1.18: A normalised sensing series across four multiplexed channels from a device functionalised with PBASE in DMSO to attach OR22a nanodiscs. Source-drain voltage was set at = 100 mV while gate voltage was set at = 0 V. The concentration of each 20 µL addition of methyl hexanoate in 1% v/v DMSO PBS is indicated above the time of addition. Current data has been despiked, baseline drift and a moving median filter applied. |

Next, an investigation was made into whether the type of solvent used in functionalisation was responsible for the variability observed in device behaviour. A solvent commonly used in the literature for functionalisation with PBASE is dimethyl sulfoxide (DMSO), as discussed in **?@sec-PBASE-attachment**. A surfactant-deposited device was functionalised with OR22a nanodiscs in the same manner as described in [Section 1.2.1](#sec-working-PBASE-functionalisation), except DMSO was used instead of methanol when preparing the PBASE solution. The sensing dataset from the four device channels of a suitable current level are displayed in [Figure 1.18](#fig-DMSO-sensing), where methyl hexanoate (MeHex) was used as the target compound. No channel shows a negative current response to MeHex. Current changes after each addition are consistently below 1% on all channels.

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The transfer characteristics of the four sensing channels are displayed in [Figure 1.19](#fig-DMSO-TX). An average threshold shift of V is seen across these channels, significantly exceeding the expected threshold shifts of for exposure to PBASE in DMSO and for exposure to DMSO without PBASE. This functionalisation threshold shift is similar to that of the device which responded to target analyte in [Section 1.2.2](#sec-EtHex-aqueous-sensing), -0.20 V. The shift is also similar to that seen for the device functionalised directly with OR22a nanodiscs without PBASE, -0.27 V. It therefore seems that the nanodiscs are directly attached to the carbon nanotube network, yet they do not respond to the target analyte. It seems likely that the negative gating is a result of nanodisc attachment to the network, either with or without PBASE as a linker; meanwhile, there is limited or no attachment between the network and the odorant receptors themselves. This lack of connection to the odorant receptors appears to be a second factor at play in the variability seen in biosensor behaviour.

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An atomic force microscope image of a film modified using DMSO in PBASE with OR22a nanodiscs is shown in [Figure 1.20](#fig-DMSO-AFM-comparison) (a), along with a mask in green indicating the average substrate height (1.8 nm). The binary representation in [Figure 1.20](#fig-DMSO-AFM-comparison) (b) shows long, rounded features sit directly above the above the CNT threshold height of 11.8 nm. By extending the threshold height range to nm, it becomes apparent that these features are not simply large carbon nanotube bundles, but instead appear to be densely packed collections of nanodisc aggregates following the length of various carbon nanotube bundles. The distribution of nanodiscs along the nanotubes gives them a ‘string of pearls’ or *Hormosira*-like appearance ([New Zealand Plant Conservation Network n.d.](#ref-NewZealandPlantConservationNetwork)). Some features are too tall for the ‘pearls’ on the ‘string’ to be individually distinguished in [Figure 1.20](#fig-DMSO-AFM-comparison) (c), but [Figure 1.20](#fig-DMSO-AFM-comparison) (d) shows that by adjusting the height threshold, the rounded ‘pearls’ along every ‘string’ correspond to separate aggregations of nanodiscs. These images strongly suggest nanodisc aggregations are present on the network, and are more densely packed along the nanotubes than in earlier images. However, this observation does not necessarily indicate a more direct connection between nanodiscs and the nanotube network.

As discussed in **?@sec-PBASE-purity**, DMSO is a highly hygroscopic solvent. If a non-negligible amount of water is present in the DMSO during functionalisation, the PBASE is being exposed to water for more than an hour before introducing OR nanodiscs. Over this time period, the PBASE may be able to undergo ester hydrolysis ([Hermanson 2013](#ref-Hermanson2013-3)). To eliminate the possibility that hydrolysis has prevented the attachment of odorant receptors to PBASE on the network, an alternative method using 1-pyrenebutyric acid (PBA) in DMSO was also trialled. This method was similar to those seen in **?@sec-PBA**. PBA is first attached to the carbon nanotube network, then, once the bulk of the DMSO has been rinsed off the device surface, converted to PBASE using carbodiimide (EDC) and succinimide (NHS) reagents. The PBASE is then available to attach to the OR22a nanodiscs as usual. The functionalisation process with PBA was therefore the same as in [Section 1.2.1](#sec-working-PBASE-functionalisation), with the following steps replacing steps :

* A solution of 5 mM PBA (Setareh Biotech) in DMSO was prepared by fully dissolving 7 mg PBASE in 5 mL DMSO by vortex mixing at 1000 rpm.
* The device was left submerged in the 5 mM PBASE in DMSO solution for 1 hour in a parafilm-sealed container.
* A solution of 20 mM EDC and 40 mM NHS in PBS was prepared by dissolving 31 mg EDC and 46 mg NHS in 10 mL PBS.

Note: EDC was thawed under vacuum for 15 minutes in dark conditions before opening.

* The device was rinsed with DMSO for 15 s and PBS for 15 s, then placed into the EDC/NHS solution for 30 minutes.
* The device was then rinsed with PBS for 15s before OR22a nanodisc functionalisation.

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| Figure 1.22: A normalised methyl hexanoate (MeHex) sensing series taken with a OR22a-functionalised carbon nanotube device using PBA with EDC and NHS. Source-drain voltage was set at = 100 mV while gate voltage was set at = 0 V. The concentration of each 20 µL addition is indicated above the time of addition. |

These steps were designed to be broadly similar to those seen in **?@sec-PBA**, with a molar excess of NHS relative to EDC to ensure full conversion of the *O*-acylisourea intermediate into PBASE. Normalised, filtered sensing series from two multiplexed channels of the functionalised device are shown in [Figure 1.22](#fig-EDCNHS-sensing). Again, any current response subsequent to additions is positive and <1%. An atomic force microscope image of a film modified in the same manner as the sensing device is shown in [Figure 1.20](#fig-DMSO-AFM-comparison) (e), with substrate height nm. When a suitable height range above the threshold height 12.6 nm is selected, as in [Figure 1.20](#fig-DMSO-AFM-comparison) (f), highly clustered nanodisc features with the appearance of pearls on a string are again visible. The transfer characteristics of each channel before and after functionalisation are shown in [Figure 1.21](#fig-EDCNHS-TX), where an average threshold shift of V is observed. In **?@sec-PBA-characterisation**, the threshold shift for PBA attachment in DMSO was -0.15 V. The difference between these two values is not large enough to convincingly conclude whether nanodiscs have attached via PBASE or not. It therefore appears that the problem identified with variability in device behaviour in [Section 1.3.1](#sec-variability-biosensor) is not resolved by the use of a different solvent or steps to prevent PBASE hydrolysis.

From this elimination process, three possible sources of variability in device performance due to nanoscale surface contamination remain. The first is the hydrocarbonaceous layer that forms due to device exposure to air, which causes channel hydrophobicity. The second is multilayer adhesion of PBASE or PBA on the transducer surface. Finally, photoresist may remain on the device channels, even despite the use of a new method which eliminates photoresist to levels invisible under a fluorescence microscope (**?@sec-photoresist-contamination**). A further possible source of variability was also identified from the PBASE in DMSO functionalisation, where transfer measurements ([Figure 1.19](#fig-DMSO-TX)) and AFM imaging ([Figure 1.20](#fig-DMSO-AFM-comparison)) each indicated that direct attachment of nanodiscs was occurring despite the device not functioning as a sensor: the possibility of minimal or no attachment of the contained odorant receptors despite nanodisc attachment. An altered non-covalent functionalisation method using pyrene-PEG-biotin was therefore developed to eliminate the confound factors identified here and investigate the resulting sensor behaviour. This novel method is trialled in the following section.

## iOR Biosensing with Aqueous Functionalisation

### Aqueous-Based Functionalisation

A carbon nanotube network field-effect transistor device, fabricated using post-June 2023 methods as described in **?@sec-fabrication**, was functionalised with a novel method using OR10a solubilised in surfactant. The odorant receptors were not expressed in a nanodisc format, and were avidin-tagged or “avi-tagged”. This eliminates the possibility of nanodiscs interfering with odorant receptor attachment, though does leave them vunerable to harsh environmental conditions ([Nath, Atkins, and Sligar 2007](#ref-Nath2007); [Bayburt and Sligar 2010](#ref-Bayburt2010)). Upon preparation, the odorant receptors were modified with pyrene-PEG-biotin. The pyrene-PEG-biotin linker attached to the avi-tags on the odorant receptors, as described in **?@sec-NTA-biotin-PEG**, allowing them to attach directly from solution to the carbon nanotubes via the attached pyrene linker. This approach meant that no PBASE, PBA or organic solvent was needed in the functionalisation process. To eliminate the remaining possible sources of surface contamination, such as the hydrocarbonaceous coating of nanotubes and residual photoresist, a short oxgyen plasma cleaning step was used.

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The details of the functionalisation, process, loosely based on the non-covalent functionalisation procedure used by Miki *et al.* ([Miki et al. 2019](#ref-Miki2019)), are as follows:

1. The device was exposed to UV light for 1 minute, placed in AZ 326 developer for 3 minutes, then rinsed with acetone, isopropanol and nitrogen dried.
2. The device was vacuum annealed for 1 hour at 150°C.

Note: Steps 1 & 2 were added to either remove or passivate residual photoresist on the channel before functionalisation, see **?@sec-photoresist-contamination**.

1. 10 µL surfactant-solubilised avi-tagged OR10a modified with pyrene-PEG-biotin (batch number AviHis-OR10a-001, prepared 12 months earlier) was diluted in 1 mL freshly-prepared PBS.

Note: The full 1 mL was used to flush out the nanodisc vial when preparing the nanodisc solution, with successive additions and subtractions of 50 µL PBS into and from the vial.

1. Device was treated with a gentle oxygen plasma, 5 W at 200-300 mTorr, for 15 seconds.

Note: Oxygen plasma was very gentle, with an O flow rate of <10 sccm into the plasma cleaner, to avoid excessive damage to the carbon nanotube network.

1. The device was submerged in the OR10a solution and left covered with parafilm for 15 minutes, then rinsed with PBS for 15 s and thoroughly nitrogen dried.

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| Figure 1.24: 1 µm 1 µm atomic force microscope image of a solvent-deposited carbon nanotube film functionalised with OR nanodiscs using Pyrene-PEG-NHS. |

[Figure 1.23](#fig-OR10a-TX-comparison) (a) shows the liquid-gated characteristics of a device channel before and after the functionalisation process with OR10a. The change of characteristics observed can be compared with the change of characteristics when plasma cleaned without further modification, seen in [Figure 1.23](#fig-OR10a-TX-comparison) (b). A significant drop in channel current occurs as a result of the plasma cleaning process. This large change in mobility makes it difficult to clearly identify changes in gating specifically due to the presence of the OR10a. The OR10a is not held within a nanodisc format, so the morphology of the functionalised network cannot be compared directly using previous atomic force microscope images. A solvent-deposited carbon nanotube film was prepared separately using OR nanodiscs, where the ORs were attached via their amine group using pyrene-PEG-NHS ester. Pyrene-PEG-NHS ester is very similar to PBASE but contains a PEG chain. [Figure 1.24](#fig-PPN-linker) shows an atomic force microscope image of the modified film. OR nanodisc aggregates very clearly follow the carbon nanotubes, indicating specific attachment between nanodiscs and carbon nanotubes can be acheived using linker containing pyrene-PEG. The presence of PEG chains may help prevent direct adsorption of proteins onto the carbon nanotubes, improving device quality and therefore sensing behaviour ([Star et al. 2003](#ref-Star2003a); [Chen et al. 2004](#ref-Chen2004)).

### Aqueous Sensing of Methyl Salicylate

The procedure used for sensing methyl salicylate (MeSal) was identical to that used in [Section 1.2.2](#sec-EtHex-aqueous-sensing), except using MeSal instead of EtHex. Analyte solutions in 0.5% DMSO/ PBS solution containing methyl salicylate concentrations at 1 fM, 1 pM, 1 nM and 1 µM were prepared beforehand, The same buffer was used for each dilution, as well as for the well, which contained 80 µL 0.5% DMSO/ PBS prior to sensing. Sensing measurements were taken using the NI-PXIe system. The full measurement sequence is shown in [Figure 1.25](#fig-MeSal-sensing) alongside gate current. remained negligible across the full sensing procedure, and no responses were seen to buffer additions or subtractions. A linear fit to the baseline drift in the region s, shown in [Figure 1.26](#fig-OR10a-sensing) (a), had a gradient of pA/s, while an exponential fit to the drift minus the linear fit, shown in [Figure 1.26](#fig-OR10a-sensing) (b), had a time constant of s. A deviation from the exponential fit similar to that seen for the control series in [Section 1.2.2](#sec-EtHex-aqueous-sensing) is observed, indicating that does not hold for the drift behaviour and further lending support to the possibility that functionalised devices exhibit characteristic long-term decay behaviour.

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| Figure 1.25: The control series (before 1800 s) and methyl salicylate sensing series (after 1800 s) of the OR10a-functionalised device channel. Source-drain voltage was set at = 100 mV while gate voltage was set at = 0 V. No responses to 0.5% v/v DMSO 1X PBS were seen during the control series, while significant responses to additions of methyl salicylate diluted in 0.5% v/v DMSO 1X PBS were seen at 2400 s and 3000 s. |

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Cleaned and filtered methyl salicylate sensing data with linear baseline drift removed is shown in [Figure 1.26](#fig-OR10a-sensing) (c). The concentration of each 20 µL methyl salicylate addition is shown above each corresponding addition time. Significant and irreversible current decreases occurred directly after the 1 fM and 1 nM MeSal additions. A 3% current drop occurred subsequent to the 1 fM addition and a 23% current drop occurred subsequent to the 1 nM MeSal addition. No negative change in current occurred after the buffer addition, or at any of the other three analyte additions. Murugathas *et al.* also observed a similar drop-off in response with increased analyte concentration when sensing with OR10a ([Murugathas et al. 2019](#ref-Murugathas2019a)). Just like the OR22a odorant receptors tested earlier, it appears that the OR10a odorant receptors saturate at the 1 nM addition, but do not show any unexplained ‘post-saturation’ activity. Transfer characteristics of the device before and after sensing are shown in [Figure 1.27](#fig-OR10a-TX-1) (a), showing a threshold shift of -0.07 V.

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The device was then rinsed for 15 s in PBS after the initial sensing series. The effect of the rinse on the transfer characteristics of the device is illustrated in [Figure 1.27](#fig-OR10a-TX-1) (b). The threshold voltage before sensing was 0.16 V. The rinsing step appears to have largely restored the electrical characteristics of the device to its state prior to sensing, bringing the threshold voltage back from 0.09 V post-sensing to 0.14 V after the rinse step. In other words, it appears the gating effect due to the presence of analyte has been reversed. Assuming that the gating effect results from structural changes in the odorant receptors, the reversal of threshold shift upon rinsing indicates that without analyte present, the proteins return to their original structure. This implies that the device can be reused as a sensor. Furthermore, as adsorption of solvent leads to gating which is not reversible through rinsing (**?@sec-PBASE-electrical-characterisation**), this is also an indication that the responses are not simply due to adsorption of the DMSO present.

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The same OR10a-functionalised device channel was then reused as a sensor subsequent to rinsing, with the full sensing run alongside gate current shown in [Figure 1.28](#fig-OR10a-responses-2) (a). In this second sensing series, only 1 nM additions of methyl salicylate were made, to explore the device behaviour at concentrations close to saturation. An irreversible current response was seen directly after all five methyl salicylate additions; the concentration in the well after each addition is shown in [Table 1.3](#tbl-concentrations-2). The expected logarithmic relationship between odorant receptor response and low concentrations of analyte is seen in [Figure 1.29](#fig-OR10a-signal-TX) (a), with a relationship constant of . As the relationship holds across all additions, it appears the presence of 500 pM MeSal is insufficient to bring odorant receptors to their saturation limit. The initial 1 nM analyte addition, bringing well concentration to 170 pM, was similar in size (24%) to the current change resulting from the 1 nM analyte addition bringing MeSal concentration to 130 pM in **?@fig-OR10a-responses** (23%). This result indicates that the relationship between response size and concentration is reproducible when the sensing channel is reused.

Table 1.3: Comparison of methyl salicylate concentration in the 20 µL additions to the total concentration of analyte in the liquid-gate electrolyte and the volume of electrolyte in the PDMS well after each addition.

| Addition # | 1 | 2 | 3 | 4 | 5 | 6 |
| --- | --- | --- | --- | --- | --- | --- |
| Addition conc. | 0 fM | 1 nM | 1 nM | 1 nM | 1 nM | 1 nM |
| Volume in well | 100 µL | 120 µL | 140 µL | 160 µL | 180 µL | 200 µL |
| Conc. in well | 0 fM | 170 pM | 290 pM | 380 pM | 440 pM | 500 pM |

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It also appears that the second sensing series resulted in a similar shift in transfer characteristics to that of the first sensing series. [Figure 1.29](#fig-OR10a-signal-TX) (b) shows a shift in threshold voltage of -0.08 V between the transfer characteristics directly before and directly after the second sensing series. The similarity between [Figure 1.27](#fig-OR10a-TX-1) (a) and [Figure 1.29](#fig-OR10a-signal-TX) (b) suggests the device gating and associated behaviour of odorant receptors was broadly similar when the sensor was used a second time, indicating a odorant receptor-functionalised device can be reused. This is surprising, given the odorant receptors lack a protective membrane. This discussion indicates that the attached odorant receptors can remain viable for at least several hours in room temperature buffer solution, without the need for the nanodisc format. The similar size of the threshold shifts seen in [Figure 1.27](#fig-OR10a-TX-1) (a) and [Figure 1.29](#fig-OR10a-signal-TX) (b) also indicates that even though it appears the odorant receptors did not saturate with the nanomolar additions of MeSal, the saturation limit was being approached. It should be noted, however, that this discussion does not account for the impact of hysteresis and current annealing on the device transfer characteristics, both of which impact the reliability of the transfer characteristic curve as an indicator of sensing.

The functionalisation method used in this section has a number of advantages over the OR nanodisc functionalisation method outlined earlier. The plasma cleaning step eliminates uncertainty stemming from a variety of possible surface coatings on the carbon nanotubes. Using detergent-solubilised odorant receptors removes the possibility that the nanodiscs are impeding direct attachment to odorant receptors in the functionalisation procedure. However, it has its own drawbacks. Oxygen plasma cleaning, even at low power, had a fairly destructive effect on the carbon nanotube network. A large drop in mobility resulted from plasma cleaning; for sparser carbon nanotube morphologies, a sizable current drop could leave a device unsuitable for sensing. Since the main advantage of non-covalent functionalisation over covalent functionalisation is its minimal impact on mobility (**?@sec-non-covalent-bonding**), this approach seems contradictory. It appears a less destructive but solvent-free approach should be identified for non-covalent functionalisation ([Ashraf et al. 2014](#ref-Ashraf2014)), or a well-established covalent approach should instead be used for attaching odorant receptors (**?@sec-sensor-types**).

### Vapour Sensing of *trans*-2-hexen-1-al

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| |  |  |  |  |  |  |  |  | | --- | --- | --- | --- | --- | --- | --- | --- | |  |  |  |  |  |  |  |  |   Figure 1.30: Back-gated carbon nanotube network device transfer characteristics on a logarithmic scale before and after modification, where the gate current for each transfer curve is shown with a dashed line. Source-drain voltage was = 100 mV for each of the forward and reverse sweep. The change in characteristics from avi-tagged OR35a functionalisation is shown in (a), while the change resulting from a 5 W plasma clean is shown in (b). |

Despite the drawbacks outlined previously, the functionalisation method in this section was also used to trial vapour phase sensing for the odorant receptor devices. The vapour pressure of methyl salicylate, 5 Pa, was too low for reliable vapour system delivery (*c.f.* **?@sec-vapour-series**) ([“Methyl salicylate - Hazardous Agents | Haz-Map” n.d.](#ref-MeSal)). The odorant receptor OR35a (batch number AviHis-OR35a-001, prepared 12 months earlier) was therefore used in the functionalisation process instead of OR10a, as it responds to *trans*-2-hexanal (E2Hex) ([Murugathas et al. 2019](#ref-Murugathas2019a)), which can be delivered successfully in the vapour system (see **?@sec-vapour-series**). Back-gated transfer characteristics of a OR35a-functionalised before and after functionalisation are shown in [Figure 1.30](#fig-OR35a-TX-comparison) (a), alongside characteristics from a device before and after plasma cleaning at 5 W without subsequent functionalisation in [Figure 1.30](#fig-OR35a-TX-comparison) (b). As expected, a significant drop in mobility is seen as a result of the plasma cleaning step. Unlike the functionalised device, the device plasma cleaned without functionalisation turns off entirely at 3 V, with this difference possibly due to variability in the results of plasma etching for different carbon nanotube devices.

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In a similar manner as in **?@sec-pristine-EtHex**, the functionalised device was back-gated in the vapour delivery system and a series of exposures to E2Hex was performed. Another pristine device channel was measured during the same sensing series for a baseline comparison. Before each series was performed, the vapour system was purged of vapour, the total dilution flow was set at 200 sccm (nominal) and flow to the PID was set to 150 sccm on the flowmeter. In line with the discussion in **?@sec-vapour-drift**, a 2500 s control series was used. The baseline drift is shown in [Figure 1.31](#fig-E2Hex-sampling) (a) and (b), with a backgate of = 0 V and a source-drain voltage of = 100 mV across the channel during each measurement. During this period, 200 sccm of nitrogen flow was placed through the device chamber. A linear fit was performed on the the measurements from each channel between s. For the pristine device, pAs, while for the OR35a-functionalised device, pAs. [Figure 1.31](#fig-E2Hex-sampling) (b) shows the exponential fit to each dataset with linear drift subtracted, where the time constant for the pristine device was s and for the OR35a-functionalised device was s.

After the 2500 s control series, each device was exposed to three intervals of *trans*-2-hexen-1-al vapour flow from the carrier line in the same manner. A total of 5 mL of the analyte of interest was present in the analyte bottle before each sensing series. A total flow of 200 sccm was kept through the chamber at all times. During each interval, 150 sccm of this total flow passed through the carrier line. Except during intervals, no flow was placed through the carrier line. A 1000 s recovery period was used between each interval. The temperature was 20°C 2°C during each series. These sensing series, which have been normalised, despiked, corrected for drift and filtered, are shown side-by-side in [Figure 1.31](#fig-E2Hex-sampling) (c). A larger current change is shown by the functionalised device than the pristine device after each addition. The PID indicated a similar concentration of E2Hex was present in the device chamber with each addition, shown in [Figure 1.32](#fig-E2Hex-additions-PID). Note that measurements were taken two days apart; the $$50% variation in chamber concentration reached with each interval is largely due to PID span drift (**?@sec-responses-to-vapour**).

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| Figure 1.32: Nominal concentration measurements by the photoionisation detector taken from the device chamber during the vapour sensing series for both pristine and OR35a-functionalised devices. The maximum nominal concentration reached during each interval of carrier flow is indicated above each peak. |

The current responses from the functionalised carbon nanotube sensor are not the sharp, clear responses to analyte of the liquid-gated device seen in [Section 1.4.2](#sec-MeSal-aqueous-sensing). There are alternative explanations for the current changes observed in [Figure 1.31](#fig-E2Hex-sampling) which do not involve specific detection of analyte. The functionalisation may have altered the drift behaviour so that the linear approximation used here for removing baseline drift is no longer useful. It may be useful for future works to incorporate computational approaches to baseline drift compensation if the linear approximation regularly breaks down for functionalised devices ([Zhang et al. 2022](#ref-Zhang2022)). The breakdown in this approximation has then led to current increases that do not directly correspond to analyte being added. The functionalisation process may also have caused the device to become more sensitive to changes in vapour concentration, increasing the signal-to-noise ratio of the sensor. Regardless of their origin, the current increases observed cannot fairly be described as clear or convincing sensing responses. A working sensor should exhibit responses more similar to those seen in [Section 1.4.2](#sec-MeSal-aqueous-sensing).

It may be necessary to ensure the sensing environment is similar to that used for aqueous sensing to achieve reliable sensing. A buffered environment may help to stabilise the unprotected odorant receptors, and so a PDMS well containing 50 µL 0.5% v/v DMSO PBS was attached to the device for vapour sensing. Despite the well being upside-down in the vapour delivery system, the hydrophobicity of the PDMS was sufficient to store the buffer securely. Current sampling over a 1 hour period in this configuration, with 200 sccm constant flow across the surface of the well, is presented in [Figure 1.33](#fig-buffer-vapour). If the well solution was leaking out of the well, the conductive liquid could form a short between the channel electrodes and backgate, prompting a large increase in gate current. However, gate current remains stable across the entire measurement period, indicating the well remains secure. Conversely, fluctuations in drain current became apparent after 800 s, and at 2400 s, the direction of baseline drift was reversed entirely. These undesirable changes appear to result from rapid evaporation of liquid in the well; when the device chamber was opened, only 10-20 µL of buffer was present.

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| Figure 1.33: Electrical samples from a carbon nanotube transistor in the vapour delivery system device chamber. Transistor voltages were = 0 V and = 100 mV. During the measurement, a PDMS well containing 50 µL 0.5% v/v DMSO 1X PBS was present on the device surface. Significant changes in baseline drift behaviour are indicated with red dotted lines. |

For readibly reproducible vapour sensing, therefore, one of two approaches present themselves. The first approach is to identify a covalent attachment mechanism that allows for specific attachment to odorant receptors via a histidine or avidin tag. This approach allows for a protective format like nanodiscs to be used in the sensing setup while eliminating concerns around unwanted attachment of the protective membrane protein. The weak nature of non-covalent binding lends itself to variable functionalisation quality and poor reproducibility. Non-covalent functionalisation may also be less suitable for use in non-aqueous environments lacking buffer stabilisation ([Li et al. 2023](#ref-Li2023)). Conversely, covalent functionalisation of mammalian-OR sensors has been used before for successful vapour sensing of eugenol ([Goldsmith et al. 2011](#ref-Goldsmith2011)). Alternatively, a similar process to the one investigated here could be used. This non-covalent approach would require the development of a highly reproducible cleaning process, able to remove a variety of organic contaminants from the carbon nanotube surface prior to functionalisation. Furthermore, a liquid capture layer which is both biofriendly and has a low vapour pressure may need to be identified and used. Ideally, this liquid would be miscible with a wide range of substances, but repel PDMS. Further discussion of potential capture layers can be found in **?@sec-future-work-vapour**.

## Conclusion

A carbon nanotube device was non-covalently functionalised using PBASE in methanol with OR22a nanodiscs and operated as a biosensor in an aqueous environment. Real-time conductance decreases of up to 45% across the sensor channel were observed in response to analyte additions, which varied logarithmically at low analyte concentrations. Short-term drift behaviour was found to be similar to that of pristine devices, where the fast-decay exponential had a time constant of s, but it appears functionalisation may affect long-term baseline drift. Other changes resulting from sensor functionalisation included a device threshold voltage shift of V and an increase in network height of up to 23 nm, both resulting from the presence of nanodiscs on the network. Additionally, to confirm the presence of odorant receptors on device channels post-functionalisation, ORs were tagged with green fluorescent protein and fluorescence microscope images taken. The functionalised channels showed significantly more green fluorescence than the control, which indicates that protein attachment to the channel is not limited to empty nanodiscs.

However, the use of the functionalisation procedure with PBASE in methanol and OR22a in nanodiscs was not readily reproducible. A repeat of the functionalisation procedure and sensing procedure across six different device channels showed no decrease in current subsequent to additions ranging from 1 fM to 1 µM. Further control testing indicated that the successful sensing seen earlier was not spurious, meaning that the lack of reproducibility could be attributed to the functionalisation procedure. Device characterisation showed that although nanodiscs appeared to be present on the channel, with a change in network height above the substrate of up to nm relative to a pristine film, the average threshold shift was V, the same as that of a device functionalised using PBASE in methanol without subsequent exposure to nanodiscs. A control taken without using PBASE also showed nanodiscs present on the channel, but resulted in a threshold shift of -0.27 V. It therefore appears that while nanodiscs are present, they are blocked off from the network in a way that prevents them from altering the electrical characteristics of the channel.

Potential confounding variables identified in the functionalisation process included coatings of surfactant, solvent, photoresist, multilayered or hydrolysed PBASE, and the atmospheric long-chain alkanes which cause carbon nanotube hydrophobicity. Several possible confounding variables were individually eliminated by making slight changes to the fabrication and functionalisation of the device. Neither changing the morphology of the carbon nanotube network or using a graphene device led to a operational sensor. Furthermore, the average threshold shift for the highly-bundled device after functionalisation was V, indicating a lack of electrical contact between the channel and nanodiscs even without surfactant present. By changing the solvent used for functionalisation from methanol to DMSO, the average threshold shift was V, which demonstrates electrical contact with the nanodiscs. However, no negative current changes were observed subsequent to analyte additions, suggesting multiple confounding factors are at play. To ensure that the hygroscopic DMSO was not hydrolysing the PBASE and preventing odorant receptor attachment, a PBA with EDC/NHS functionalisation method was used. However, the average threshold shift observed was V, similar to the -0.15 V shift seen for attachment of PBA to DMSO without subsequent modification. The confounding factor is therefore not resolved by either changing the solvent or through the prevention of hydrolysis.

The remaining possible sources of surface contamination, including alkane hydrocarbons, multilayer linker and photoresist, were then addressed by making significant changes to the functionalisation procedure. To avoid multilayer coverage, pyrene-PEG-biotin was attached to avi-tagged odorant receptors before functionalisation. To remove hydrocarbons and residual photoresist, the transducer device was gently oxygen plasma cleaned before functionalisation. Furthermore, no nanodiscs were used, to ensure direct attachment of odorant receptors. Although there are also issues with reliable reproducibility of this method due to the plasma cleaning step, when a device was functionalised with OR10a in this manner, device current decreases of up to 24% were observed in response to methyl salicylate additions. It was found that rinsing the device meant the sensors transfer characteristics were restored, and the device could be reused. When reusing the sensor, a logarithmic relationship was observed between picomolar concentrations of methyl salicylate in the well and the sensor current response, with a relationship constant of .

This aqueous functionalisation approach was also used for vapour sensing with OR35a odorant receptors. Clear responses consistent with those seen in an aqueous environment were not observed. The changes in current seen appear more likely to result from a breakdown of the linear approximation of baseline drift for functionalised devices, or from increased non-specific sensitivity of the device post-functionalisation. It was concluded that reproducible vapour sensing would require either a robust covalent functionalisation method which used a protective membrane-like format, or alternatively requires a capture layer to protect non-covalently attached odorant receptors from the harsh chamber environment. However, it was found 0.5% v/v DMSO PBS could not act as this capture layer, due to rapid evaporation of the layer dramatically altering baseline drift from 800 s onwards. An alternative liquid should therefore be identified which is biofriendly and miscible, while having a low vapour pressure (ideally Pa at room temperature). It should also repel PDMS, to remain contained in the PDMS well upside down in the device chamber. These approaches significantly expand the scope of this work, and are therefore not addressed extensively in this thesis. However, some preliminary work on alternative approaches is discussed in **?@sec-future-work**.

# Vapour System Hardware

Table A.1: Major components used in construction of the vapour delivery system described in this thesis.

| Description | Part No. | Manufacturer |
| --- | --- | --- |
| Mass flow controller, 20 sccm full scale | GE50A-013201SBV020 | MKS Instruments |
| Mass flow controller, 200 sccm full scale | GE50A-013202SBV020 | MKS Instruments |
| Mass flow controller, 500 sccm full scale | FC-2901V | Tylan |
| Analogue flowmeter, 240 sccm max. flow | 116261-30 | Dwyer |
| Micro diaphragm pump | P200-B3C5V-35000 | Xavitech |
| Analogue flow controller, for micro diaphragm pump | X3000450 | Xavitech |
| 10 mL Schott bottle | 218010802 | Duran |
| PTFE connection cap system | Z742273 | Duran |
| Baseline VOC-TRAQ flow cell, purple | 043-950 | Ametek Mocon |
| Baseline VOC-TRAQ flow cell, red | 043-951 | Ametek Mocon |
| Humidity and temperature sensor | T9602-5-A | Telaire |
| Enclosure, for humidity and temperature sensor | MC001189 | Multicomp Pro |

# Python Code for Data Analysis

## Code Repository

The code used for general analysis of field-effect transistor devices in this thesis was written with Python 3.8.8. Contributors to the code used include Erica Cassie, Erica Happe, Marissa Dierkes and Leo Browning. The code is located on GitHub and the research group OneDrive, and is available on request.

## Atomic Force Microscope Histogram Analysis

The purpose of this code is to analyse atomic force microscope (AFM) images of carbon nanotube networks in .xyz format taken using an atomic force microscope and processed in Gwyddion (see **?@sec-afm-characterisation**). It was originally designed by Erica Happe in Matlab, and adapted by Marissa Dierkes and myself for use in Python. The code imports the .xyz data and sorts it into bins 0.15 nm in size for processing. To perform skew-normal distribution fits, both *scipy.optimize.curve\_fit* and *scipy.stats.skewnorm* modules are used in this code.

## Raman Spectroscopy Analysis

The purpose of this code is to analyse a series of Raman spectra taken at different points on a single film (see **?@sec-raman-characterisation**). Data is imported in a series of tab-delimited text files, with the low wavenumber spectrum (100 cm cm) and high wavenumber spectrum (1300 cm cm) imported in separate datafiles for each scan location.

## Field-Effect Transistor Analysis

The purpose of this code is to analyse electrical measurements taken of field-effect transistor (FET) devices. Electrical measurements were either taken from the Keysight 4156C Semiconductor Parameter Analyser, National Instruments NI-PXIe or Keysight B1500A Semiconductor Device Analyser as discussed in **?@sec-electrical-characterisation**; the code is able to analyse data in .csv format taken from all three measurement setups. The main Python file in the code base consists of three related but independent modules: the first analyses and plots sensing data from the FET devices, the second analyses and plots transfer characteristics from channels across a device, and the third compares individual channel characteristics before and after a modification or after each of several modifications. The code base also features a separate config file and style sheet which govern the behaviour of the main code. The code base was designed collaboratively by myself and Erica Cassie over GitHub using the Sourcetree Git GUI.

# References

Ashraf, Ali, Yanbin Wu, Michael C. Wang, Narayana R. Aluru, Seyed A. Dastgheib, and Sung Woo Nam. 2014. “Spectroscopic investigation of the wettability of multilayer graphene using highly ordered pyrolytic graphite as a model material.” *Langmuir* 30 (43): 12827–36. <https://doi.org/10.1021/LA503089K/SUPPL_FILE/LA503089K_SI_001.PDF>.

Bayburt, Timothy H., and Stephen G. Sligar. 2010. “Membrane protein assembly into Nanodiscs.” *FEBS Letters* 584 (9): 1721–27. <https://doi.org/10.1016/J.FEBSLET.2009.10.024>.

Bradley, K., M. Briman, A. Star, and G. Gruner. 2004. “Charge Transfer from Adsorbed Proteins.” *Nano Letters* 4 (2): 253–56. <https://doi.org/10.1021/NL034985>.

Cao, Qing, and John A. Rogers. 2009. “Ultrathin Films of Single-Walled Carbon Nanotubes for Electronics and Sensors: A Review of Fundamental and Applied Aspects.” *Advanced Materials* 21 (1): 29–53. <https://doi.org/10.1002/ADMA.200801995>.

Cheema, Jamal Ahmed, Nihan Aydemir, Colm Carraher, Roshan Khadka, Damon Colbert, Harris T. Lin, Andrew Nelson, Andrew Kralicek, and Jadranka Travas-Sejdic. 2021. “Insect odorant receptor nanodiscs for sensitive and specific electrochemical detection of odorant compounds.” *Sensors and Actuators, B: Chemical* 329 (February). <https://doi.org/10.1016/J.SNB.2020.129243>.

Chen, Robert J., Hee Cheul Choi, Sarunya Bangsaruntip, Erhan Yenilmez, Xiaowu Tang, Qian Wang, Ying Lan Chang, and Hongjie Dai. 2004. “An Investigation of the Mechanisms of Electronic Sensing of Protein Adsorption on Carbon Nanotube Devices.” *Journal of the American Chemical Society* 126 (5): 1563–68. <https://doi.org/10.1021/JA038702M>.

Goldsmith, Brett R., Joseph J. Mitala, Jesusa Josue, Ana Castro, Mitchell B. Lerner, Timothy H. Bayburt, Samuel M. Khamis, et al. 2011. “Biomimetic chemical sensors using nanoelectronic readout of olfactory receptor proteins.” *ACS Nano* 5 (7): 5408–16. <https://doi.org/10.1021/NN200489J/SUPPL_FILE/NN200489J_SI_001.PDF>.

Heller, Iddo, Anne M. Janssens, Jaan Männik, Ethan D. Minot, Serge G. Lemay, and Cees Dekker. 2008. “Identifying the mechanism of biosensing with carbon nanotube transistors.” *Nano Letters* 8 (2): 591–95. <https://doi.org/10.1021/NL072996I>.

Hermanson, Greg T. 2013. “The Reactions of Bioconjugation.” *Bioconjugate Techniques*, January, 229–58. <https://doi.org/10.1016/B978-0-12-382239-0.00003-0>.

Kauffman, Douglas R., and Alexander Star. 2008. “Electronically monitoring biological interactions with carbon nanotube field-effect transistors.” *Chemical Society Reviews* 37 (6): 1197–1206. <https://doi.org/10.1039/B709567H>.

Khadka, Roshan, Nihan Aydemir, Colm Carraher, Cyril Hamiaux, Damon Colbert, Jamal Cheema, Jenny Malmström, Andrew Kralicek, and Jadranka Travas-Sejdic. 2019. “An ultrasensitive electrochemical impedance-based biosensor using insect odorant receptors to detect odorants.” *Biosensors and Bioelectronics* 126 (February): 207–13. <https://doi.org/10.1016/J.BIOS.2018.10.043>.

Li, Zhongyu, Mengmeng Xiao, Chuanhong Jin, and Zhiyong Zhang. 2023. “Toward the Commercialization of Carbon Nanotube Field Effect Transistor Biosensors.” *Biosensors 2023, Vol. 13, Page 326* 13 (3): 326. <https://doi.org/10.3390/BIOS13030326>.

“Methyl salicylate - Hazardous Agents | Haz-Map.” n.d. Accessed May 21, 2024. [https://haz-map.com/Agents/6143?referer=Search\&referer\_data[s]=methyl+salicylate\&return\_url=\%2FSearch\%3Fdofilter\%3D1\%26f\%255Bpagesize\%255D\%3D25\%26f\%255Bsortby\%255D\%3D\%26f\%255Bsortdir\%255D\%3D\%26f\%255Btab\%255D\%3Dtab1\%26f\%255Bs\%255D\%3Dmethyl\%2Bsalicylate](https://haz-map.com/Agents/6143?referer=Search\&referer_data%5bs%5d=methyl+salicylate\&return_url=\%2FSearch\%3Fdofilter\%3D1\%26f\%255Bpagesize\%255D\%3D25\%26f\%255Bsortby\%255D\%3D\%26f\%255Bsortdir\%255D\%3D\%26f\%255Btab\%255D\%3Dtab1\%26f\%255Bs\%255D\%3Dmethyl\%2Bsalicylate).

Miki, Hiroko, Atsunobu Isobayashi, Tatsuro Saito, and Yoshiaki Sugizaki. 2019. “Ionic liquids with wafer-scalable graphene sensors for biological detection.” *IEEE Transactions on Nanobioscience* 18 (2): 216–19. <https://doi.org/10.1109/TNB.2019.2905286>.

Murugathas, Thanihaichelvan, Cyril Hamiaux, Damon Colbert, Andrew V. Kralicek, Natalie O. V. Plank, and Colm Carraher. 2020. “Evaluating insect odorant receptor display formats for biosensing using graphene field effect transistors.” *ACS Applied Electronic Materials* 2 (11): 3610–17. <https://doi.org/10.1021/ACSAELM.0C00677>.

Murugathas, Thanihaichelvan, Han Yue Zheng, Damon Colbert, Andrew V. Kralicek, Colm Carraher, and Natalie O. V. Plank. 2019. “Biosensing with Insect Odorant Receptor Nanodiscs and Carbon Nanotube Field-Effect Transistors.” *ACS Applied Materials and Interfaces* 11 (9): 9530–38. <https://doi.org/10.1021/ACSAMI.8B19433>.

Nath, Abhinav, William M. Atkins, and Stephen G. Sligar. 2007. “Applications of phospholipid bilayer nanodiscs in the study of membranes and membrane proteins.” *Biochemistry* 46 (8): 2059–69. <https://doi.org/10.1021/BI602371N>.

New Zealand Plant Conservation Network. n.d. “Hormosira banksii.” Accessed April 9, 2024. <https://www.nzpcn.org.nz/flora/species/hormosira-banksii/>.

Persaud, Krishna, and George Dodd. 1982. “Analysis of discrimination mechanisms in the mammalian olfactory system using a model nose.” *Nature 1982 299:5881* 299 (5881): 352–55. <https://doi.org/10.1038/299352a0>.

Star, Alexander, Jean Christophe P. Gabriel, Keith Bradley, and George Grüner. 2003. “Electronic detection of specific protein binding using nanotube FET devices.” *Nano Letters* 3 (4): 459–63. <https://doi.org/10.1021/NL0340172>.

Vobornik, Dusan, Maohui Chen, Shan Zou, and Gregory P. Lopinski. 2023. “Measuring the Diameter of Single-Wall Carbon Nanotubes Using AFM.” *Nanomaterials* 13 (3): 477. <https://doi.org/10.3390/NANO13030477>.

Zhang, Chao, Wen Wang, Yong Pan, Lina Cheng, Shoupei Zhai, and Xu Gao. 2022. “A two-stage method for real-time baseline drift compensation in gas sensors.” *Measurement Science and Technology* 33 (4): 045108. <https://doi.org/10.1088/1361-6501/AC491F>.