

1 Introduction

In this section, I will outline the steps taken to achieve reliable surface photovoltage (SPV) measurements as a function of temperature.

In the Cahen group, three Kelvin Probes (KPs) are in use. One measures in ambient, in a humidity controlled room (20% relative humidity), one in a controlled nitrogen atmosphere inside a glove box (ideally $< 5\text{ppm } O_2 \text{ \& } H_2O$). Those two are in-house built and use probe-heads manufactured by Besoke. The last one, situated inside a Lakeshore cryogenic system, is built by Mc Allister and can measure in ambient under argon atmosphere & in vacuum, with temperature dependence. It originally uses a probe head provided by Mc Allister but was complemented by in-house designed probe-heads to allow for SPV-measurements.

A standard reference with known and stable work-function, HOPG, is used to calibrate the probe, i.e. to find the work function of the probe head. To compare CPD-measurements of the three probes, Si-H was used as a relatively stable and well understood sample. To compare SPV-measurements, aluminium was deposited onto Si-H by atomic layer deposition (ALD), resulting in an alumina-coated samples. These were measured in ambient and in the Mc Allister. Vanadium-dioxide samples were used as a proof of concept for the measurements of the surface-photovoltage as a function of temperature.

2 Theory

2.1 The Contact Potential Difference and the Kelvin Probe

When two (semi-)conductors with dissimilar Fermi levels are electrically connected from their back-side with a gap between them, charge will flow from the material with the lower work function (WF) to the one with the higher WF. The work function is defined as the energy needed to remove an electron from a solid to a point in vacuum immediately outside of it. Electrons will stop flowing when equilibrium is established. As long as there is a gap between the materials, an electrical field will develop in the gap due to the difference in the local vacuum level across this gap. The potential drop across the gap, the contact potential difference or CPD. When the work functions are expressed in Electron-Volts, the CPD is directly equal to the difference of the WFs:

$$\text{CPD} \equiv \varphi_{\text{Probe}} - \varphi_{\text{Sample}} . \quad (1)$$

The order of the operands in the equation above is a matter of convention. Their physical representation depends on how the measurement system which we will investigate in the following – the Kelvin Probe – is set up electrically. In the configuration outline above, the materials behave like a parallel plate capacitor and a capacitance is established, which is known to be:

$$C(t) = \frac{\epsilon\epsilon_0 A}{d(t)} \quad (2)$$

in which ϵ & ϵ_0 are the permittivity and the permittivity of free-space respectively, A is the area of the parallel plate and $d(t)$ is the distance between the plates. $d(t)$ is taken as a function of time, because the Kelvin Probe varies the distance in time. The current between the plates is given by the change in charge on the plates, which is in turn given by the change in capacitance:

$$I(t) = \frac{dQ}{dT} = \Delta V \frac{dC}{dV} , \quad (3)$$

where ΔV is the difference in potential between the plates, which is the sum of the applied backing voltage and the naturally occurring potential difference between the plates, the CPD:

$\Delta V = V_{\text{Backing}} + \text{CPD}$. If we assume a sinusoidally varying distance with the average distance between the plates being d_0 , d_1 being the amplitude of oscillation, ω being its frequency of oscillation and an arbitrary phase ψ , then

$$d(t) = d_0 + d_1 \sin(\omega t + \psi) \quad (4)$$

and finally

$$I(t, \Delta V) = -\epsilon \epsilon_0 A \Delta V \frac{d_1 \omega \cos(\omega t + \psi)}{(d_0 + d_1 \sin(\omega t + \psi))^2}. \quad (5)$$

In equation (5), the current is written as a function of time and potential difference between the plates, because while continuously varying the distance between probe and sample, the Kelvin Probe also varies V_{Backing} . As can easily be seen from equation (5), the current is zero or 'nulled' when $V_{\text{Backing}} = -\text{CPD}$. Thus, if ϕ_{Probe} is known, ϕ_{Sample} can easily be calculated from equation (1). In practice, this requires calibrating the probe head against a sample with known work function, HOPG in the context of this study. Obviously, if one wants to study the work function of a sample as a function of temperature, the temperature dependence of the work function of the probe also has to be known. In most cases and especially for simple metals, the work function only varies over a few hundredths to a few tenths of meVs per Kelvin [1, 2, 3, 4, 5]. These variations are negligible compared to other sources of experimental uncertainty and the work function of the probe is therefore assumed to be constant with respect to temperature throughout this work. As pointed out, the work function WF of a semiconductor is defined as the the energy needed to remove an electron from the material to a point in vacuum just outside of it and is given by the difference of the near surface vacuum energy E_{vac} and the Fermi energy E_f of the material: $WF = E_{\text{vac}} - E_f$. The Fermi level of a doped semiconductor is dependent on the temperature and the carrier-concentrations of the semiconductor and can be expressed in terms of the intrinsic Fermi energy as:

$$E_{f,n} = E_i - kT \ln \frac{n}{n_i} \quad (6) \quad \text{and} \quad E_{f,p} = E_i + kT \ln \frac{p}{p_i} \quad (7),$$

for n- and p-type semiconductors respectively. As can be seen from the preceding equations, E_f changes with the Boltzmann Temperature. At 300 K ¹ and at 100 K, kT is approximately equal to 26 and 8.6 meV, respectively. In many cases, it is assumed that the extrinsic carrier concentrations n and p are equal to the product of dopant concentration and number of supplied free carriers per dopant atom. But even in that case, the concentration of intrinsic carriers is still a strong function of temperature and requires knowledge of several material parameters to calculate precisely. A simpler argument that is valid for moderately doped semiconductors in which the Fermi-Dirac distribution can be approximated by the Boltzmann distribution is developed in the following for the example of an n-type semiconductor. In such a semiconductor, the chance of finding an electron close to the conduction band edge is greater than finding a hole close to the valence band edge. Therefore, the Fermi level is closer to the conduction band. At absolute zero, all levels below the Fermi level are filled and all levels above the Fermi level are empty, by definition. At absolute zero, there can be no free electrons as freedom to move would imply energy. Therefore, at absolute zero, the Fermi level cannot be above the conduction band edge. So far, it is shown that the Fermi level must be closer to the conduction band, but below its band edge. At extremely high temperatures, doping will be negligible because thermally generated carriers will exceed carriers introduced by the dopant. Therefore, the Fermi level will tend toward the intrinsic Fermi level in mid gap. A similar argument holds for the Fermi level of a moderately doped p-type semiconductor and it is therefore shown that:

¹approximately room temperature

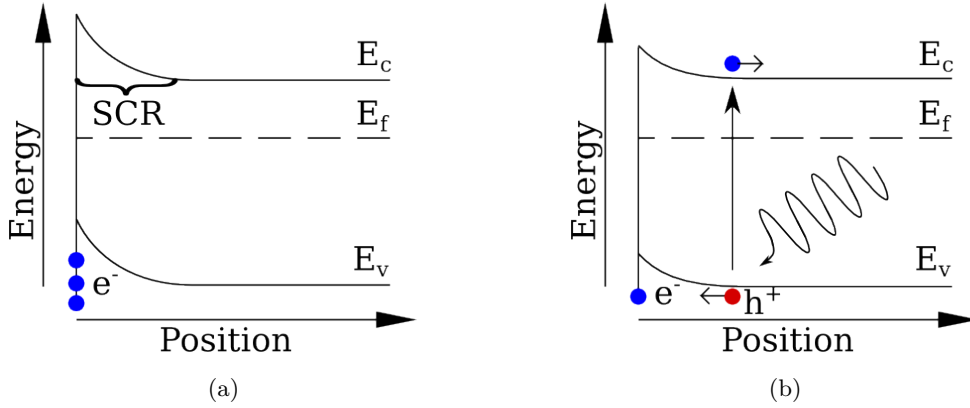


Figure 1: Band bending, trapped surface charges and the space charge region at the surface of an n-type semiconductor (a) in the dark and (b) under illumination. Note the decrease in trapped surface charges in (b) and the resulting reduction in band bending. Energy levels of the valence band, E_v , the Fermi level, E_f , and the conduction band, E_c , are included for reference.

$$\frac{dE_{f,n}}{dT} < 0 \quad (8) \quad \text{and} \quad \frac{dE_{f,p}}{dT} > 0 \quad (9),$$

for the Fermi level of an n-type and a p-type semiconductor, respectively.

2.2 The Surface Photovoltage and Band Bending

In the context of this work, the surface photovoltage (SPV) is defined as the CPD measured under illumination minus the CPD in the dark:

$$SPV \equiv \text{CPD}_{\text{light}} - \text{CPD}_{\text{dark}}. \quad (10)$$

It is instructive to refer to the diagrams in Figure 1 to understand the origin of the surface photovoltage: in the dark, majority carriers are trapped at the surface, setting up a space charge region (*SCR*). For n-type semiconductors, electrons are in the majority, accumulating negative charge on the surface, setting up an electrical field pointing from the bulk toward the surface. This field causes the potential energy of electrons to be higher at the surface than in the bulk and accordingly, the bands in Figure 1a are bent 'up'. Of course, the situation is reversed for p-type semiconductors. Under illumination, electron-hole pairs are created where radiation of sufficient energy is absorbed. For direct band-gap semiconductors, the absorption depth is shallow and electron-hole pair generation might well occur within the *SCR*. For indirect band-gap materials, absorption might occur deep within the bulk and carriers might have to diffuse through the material until they reach the *SCP*. Regardless of their path, once the carriers are close to or within the *SCR* the direction of the electrical field present there causes minority carriers to be attracted to the surface and majority carriers to be repulsed back to the bulk. Once the minority carriers reach the surface, they will recombine with majority carriers already present there. This causes the charge at the surface to decrease and the bands to flatten, see Figure 1b. When the trapped surface charge is completely neutralised, the bands will return to their initial flat state, the *SCR* will vanish and it is said that the SPV has saturated [6]. Saturation is usually assumed in an experiment when a further increase in illumination intensity does not lead to a further change in

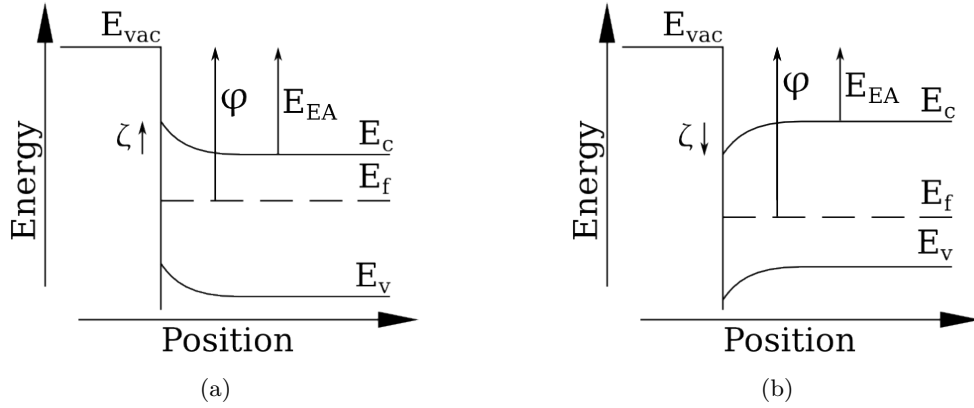


Figure 2: Definition of terms electron affinity, E_{EA} , band-bending ζ , conduction band edge, E_c , Fermi level, E_f and work function, ϕ , for an n-type semiconductor (a) and a p-type semiconductor (b). It can be clearly seen that the band bending is negative for the p-type semiconductor. Valence band edge, E_v , included for reference.

observed light CPD. For this reason, SPV is often the method of choice when investigating the band bending [7, 8] but it should be noted that in the presence of strong Fermi level pinning, bands might still be bent, even if SPV saturation is reached [9]. In that case, bending is not exclusively due to trapped charges and care should be taken when analysing results obtained by SPV. In a metal, the Fermi level lies within the conduction band. Therefore, carriers are free to move to and from the surface and no notable SCR will exist in a metal. Therefore, no difference in CPD between the dark and the illuminated condition is expected for a metal, so equations (1) and (10) combine to give the SPV as a function exclusively in terms of the sample material:

$$SPV = \phi_{s,dark} - \phi_{s,light} . \quad (11)$$

To gain a deeper insight into the behaviour of a semiconductor as it reacts to light, its work function can be redefined in more practical terms, namely in terms of electron affinity, band-bending, conduction band edge and Fermi level, which are shown in Figure 2. Here, electron affinity is defined as the energy obtained by moving an electron from vacuum just outside the semiconductor to the bottom of the conduction band edge deep inside the semiconductor, which is subtly different from its usual definitions in Chemistry and Solid State Physics ². We have:

$$E_{EA} \equiv E_{vac} - E_c . \quad (12)$$

Band-bending, ζ , is the difference in energy of the conduction band close to the semiconductor surface and deep within the semiconductor, so the work function can be given by

$$\phi = E_{EA} + E_c - \zeta - E_f . \quad (13)$$

In the equation above, E_{EA} and E_c are not affected by illumination, band-bending vanishes under saturation ³ and E_f can change because of its dependence on the carrier concentrations as

²In Solid State Physics E_{EA} is usually defined as the energy gained by moving an electron from vacuum just outside the material to the conduction band close to the surface, because this quantity is experimentally accessible. Our definition gives access to the band-bending, ζ , as an independent parameter.

³in the absence of Fermi level pinning

expressed in equations (6) and (7). However, if its change due to illumination is for the moment assumed to be small compared to the band bending, then combining equations (13) and (11) yields an interesting property of the SPV: its sign can be used to identify if a sample is n- or p-type. For an n-type semiconductor, ζ is positive and thus its SPV is also a positive quantity; for a p-type semiconductor, the situation is reversed: both ζ and SPV are negative.

3 Kelvin Probes in use

3.1 The Lakeshore Cryogenic System coupled with a Mc Allister Kelvin Probe

Lakeshore is an international vendor of cryogenic probe stations. For this research, a Lakeshore Model TTPX Probe Station was used. The probe station can be thought of as being divided into four components. An outer vacuum-chamber is connected to a pump to reduce the pressure inside the station. An Argon gas inlet connected to the vacuum chamber can be used to provide an inert atmosphere. Inside the vacuum chamber is a separate, smaller chamber: the radiation shielding stage, primarily used to shield the sample from infrared radiation and thus used to facilitate measurements at low temperatures. The radiation shielding to some extent also provides electrical shielding from stray electrical signals and can therefore act as a quasi Faraday-cage. Both these chambers are fitted with windows to allow for placement of the probe-arms and to allow for visual inspection of the experiment. The radiation shielding stage's windows is made from sapphire glass, as sapphire glass is oblique to infra-red radiation. Inside the shielding stage is placed the sample stage, which allows for mounting of samples and can provide an electrical "ground". The fourth and last component of the probe station are its six probe-arms. They allow for placement of several probes on the sample from the outside. For many measurements, these probes are conceptually simple gold wires which allow for electrical measurements of the sample, such as IV and CV characterisation. Being a cryogenic system, the Lakeshore is fitted with three thermocouples. They measure the temperature of the sample stage, the radiation chamber and the probe-arm respectively. The temperature is adjusted by an electrical heater and by controlling the flow of coolant, either liquid nitrogen or – to achieve lower temperatures – liquid helium. Evacuation of the cryogenic system is achieved by a combination of two pumps: a 'weak pump' to reduce the pressure to $\sim 5 \cdot 10^{-2}$ and a 'turbo pump' to reduce it down to $\sim 5 \cdot 10^{-4}$. A schematic of the Lakeshore model TTPX cryogenic system showing its components is given in Figure 3.

In our case, one of the probe arms is fitted with a modified Mc Allister Ultra-High-Vacuum Kelvin Probe Head. The original Mc Allister UHV Kelvin probe head is a horizontal base-arm ending in a vibrating, stainless steel cylinder of 2.6 mm diameter ending in a continuous, flat disk. This disk forms one of the two capacitor plates necessary for a CPD measurement. The other capacitor is, of course, the sample. Using the Mc Allister, the measured signal is given by equation (1) i.e. the signal is equal to the work function of the probe head, usually $\approx 4.5\text{eV}$, minus the work function of the sample. A reduction in measured CPD therefore means an increase in the sample's work function.

The original probe head configuration is not suitable for the Lakeshore cryogenic system because the sample needs to be placed horizontally onto the sample-stage. Therefore, a vertical geometry is needed for the probe-head. Such a custom system was provided by Mc Allister. The stainless-steel Kelvin probe head is now vertically mounted in a plastic base. The size and especially the weight-distribution of the original cylinder are carefully designed by Mc Allister to comply with a vibration-response that is suitable for the probe head controller. The probe head is electrically connected by a gold wire that runs along the base-arm and is either soldered directly onto the cylinder or tightly wrapped around a conductive screw which is used to hold the probe head in

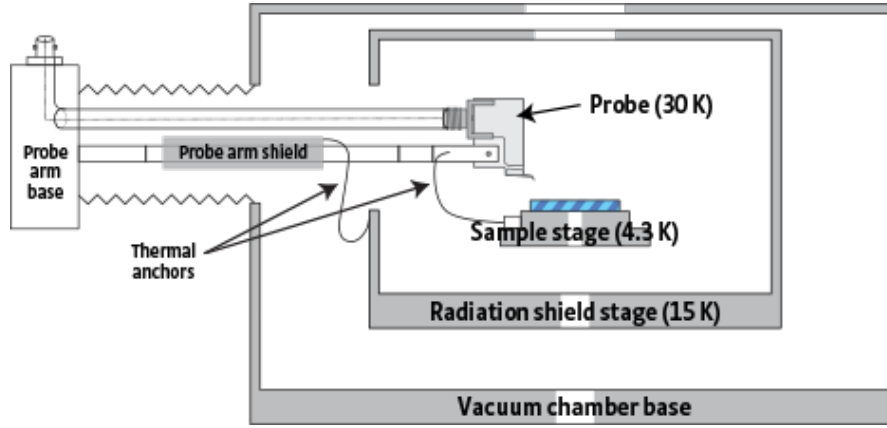


Figure 3: Schematic of the Lakeshore model TTPX cryogenic system and its components, typical operational temperatures are indicated. Taken from the vendor's website [10].

place in its plastic holder. In the latter case, conductive silver paste suitable for UHV environments is applied to the screw to ensure low resistance electrical connection. Contact potential difference measurements are severely negatively affected by non-ohmic back contacts. A second probe arm of the cryogenic system was fitted with an optical fibre to allow for laser illumination of the sample. However, in practice, it quickly became clear that such an illumination set-up was unsuitable for SPV measurements. This was due to several reasons. For suitable CPD measurements, the probe head needs to be brought in very close proximity to the sample: distances on the scale of a few hundred micrometers are often necessary to obtain a sufficiently noise-free signal⁴. Therefore, there is simply not enough room for the exit of the optical fibre to be placed in a position where light would illuminate the sample. A further difficulty of the fibre illumination scheme are noticeable reductions in light intensity due to absorption in the fibre. After all, the fibre needs to be able withstand vacuum conditions and low temperatures, limiting the choice of suitable materials. Lastly, the fibre would provide a very localised spot of illumination. For a successful measurement of the SPV, the whole area under the probe head has to be saturated by illumination at the very least. Full saturation of the whole sample surface is in most cases desirable to suppress unwanted carrier recombination in the dark areas. For these reasons, it was decided to modify the probe head and employ a different illumination scheme. The cryogenic system's windows allow for illumination by a source of light placed outside the vacuum chamber, on top of the external window, focused onto the sample surface. To allow this scheme to work, the main body of the probe head needed to be hollowed out and holes needed to be drilled into the head's disk to let light pass through and onto the sample. Such a probe head, manufactured from stainless steel, was provided by Mc Allister and used in initial experiments. When successful measurements were not forthcoming, three further modifications of the probe head were tried, all based on the same principle. The idea was to replace the massive disk with a wire-grid used for transmission electron microscopy. Three different types of wire-grids were purchased from ????. A stiff, stainless steel grid with XX% opacity, two thin, flexible gold grids with XX and XX% opacity respectively. The grids were laser-welded onto custom-made, hollowed out stainless steel cylinders. These new probe heads were manufactured by the Weizmann Institute's Department for Construction and Engineering. Care was taken to ensure acoustic vibration characteristics of

⁴This adds to the practical danger of involuntarily crashing the vibrating probe head onto the sample, potentially damaging the sample, contaminating the probe head and generally interfering with conducting an experiment

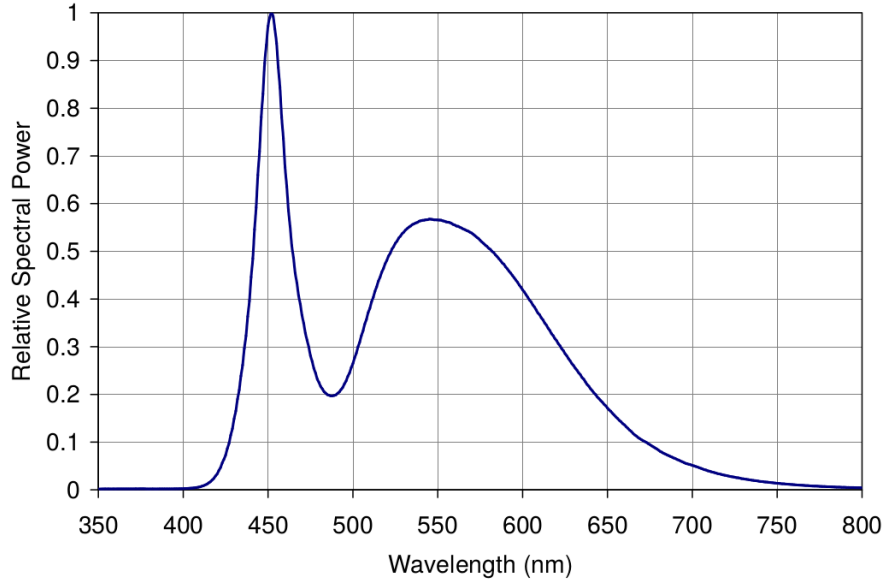


Figure 4: Typical relative spectral intensity of the LEDengin LED at an operating temperature of 25° C, taken from the vendor’s supplementary information [11, p. 10].

the new probe heads were similar, if not identical to those of the original Mc Allister probe heads. The wire-grids would add two benefits: they would increase the overall transmission of the probe head as well as allow for a more even illumination of the sample surface. In practice, however, no immediate, significant difference between the performance of the original hollow stainless steel probe head and the new, TEM wire-grid heads was found. At this point, an inherent limitation of the adopted illumination scheme has to be pointed out: namely that even in the ideal case, illumination from above will only result in an illuminated area directly under the probe head. The probe arm, probe head holder and even the edge of the hollow cylinder will all cast a shadow on the sample, especially since they need to be placed directly above it.

In order to allow for saturating illumination of the sample, the choice of light source is crucial and it was thus a main focus of this part of the project to identify such a source and to successfully connect it to the combination of Lakeshore cryogenic station and Mc Allister Kelvin Probe. Successful SPV measurements are routinely carried out in the group using the ambient Kelvin Probe. This probe uses a xenon-lamp driven by a VariAC-power source with up to 60 W electrical power. The xenon-lamp is not only a source of light, but also a source of heat and thus unsuitable for the temperature-dependent measurement inside the Mc Allister. Not only would the heat introduce uncertainties in temperature but temperature gradients introduced by it could also damage the cryostation, specifically the radiation shielding stage’s sapphire window. Therefore, the choice fell upon a high intensity, natural-white light LED manufactured by LED Engin, model LZP-00CW0R. The LEDengin LED uses 25 LED-spots soldered onto and electrically connected by a PCB. Using thermo-paste, the LED is mounted onto a copper-core of a discarded PC-fan. The fan-motor is driven by a small 12V AC current source to achieve the necessary cooling of the delicate LED. As purchased, the LED has a relatively wide illumination cone of 60°, due to an internal fish-eye lens that is situated right atop the PCB. Therefore, the lamp was supplemented by a total internal reflection lens by LEDEngin that focuses 90% of the illumination into a 10° wide cone. The initial LED of nominally 4200lm intensity was damaged, only 12 of 25 LED-spots

were functioning and was later replaced by new LED of the same manufacturer with 5200 *lm* intensity. The LED is driven by a variable DC source at a maximum voltage of 18.2 V and maximum current of 1.5 A. Its relative spectral intensity is given in Figure 4.

4 Measuring CPD at room temperature

4.1 Sample Preparation

A fresh surface of HOPG is prepared by gently rubbing adhesive tape onto a square piece of HOPG and tearing it off evenly. The piece is mounted onto a sample-holder using an electrically conductive clip and the CPD is measured.

n-Si-H (100) with different resistivities/doping-levels is prepared according to a slightly modified standard cleaning procedure: pieces of suitable size are cut with a diamond tip cutter, swiped off with ethyl-acetate and successively sonicated for three minutes each in ethyl-acetate, acetone, methanol and water. The pieces are microwave-treated in an O_2 -plasma at 100W with a flow of $1\text{cm}^3/\text{min}O_2$ and $1.5\text{cm}^3/\text{min}Ar$ for 3 minutes. Subsequently, samples are rinsed with pure water ($18M\Omega\text{cm}$ at 20°C), immersed in 2% HF etching solution for 1 minute, rinsed with water and ashered again as before. The pieces are etched as before, back-contacts are created by applying InGa-eutectic to a scratched back surface. The piece is mounted onto a sample holder and the CPD is measured for at least two minutes each on three different spots per piece. The time the sample is subjected to ambient after etch and before each measurement is recorded and used in a linear fit ' $\Delta(\text{CPD})/\Delta t$ ' to find the – arguably somewhat hypothetical – CPD each spot on each piece would have had right after the etch, i.e. without the time needed for creating the back surface and mounting the sample.

4.2 Results & Discussion

The standard deviation of measured CPD between spots of the same piece is comparable to that between pieces, so all obtained values were averaged. The values obtained across the three systems agree very well with each other and in the case of mid- and high-resistivity silicon also with theory, see Figure 5. A three, instead of only one, minute long HF etch did not influence the CPD obtained for the low resistivity sample. A possible explanation for the deviation from theory might be found in the increased surface-reactivity of highly doped silicon: by the time the experiments are started, the silicon surface might already be oxidised.

5 CPD as function of pressure and temperature

5.1 CPD as a function of pressure

Once it was established that results obtained from the three independent system under similar conditions using hydrogenated silicon as a reference sample, efforts were concentrated on temperature and pressure dependent measurements in the Lakeshore cryogenic system. Because of unavoidable contamination with oxygen from ambient, hydrogenated silicon was not used to that end. Instead, a freshly prepared reference of HOPG was placed on the ground of the radiation shielding stage without a sample-mount. An electrically conductive screw and clip were used to connect the top of the HOPG sample to the electrical ground of the Lakeshore. Two sets of experiments were carried out to independently determine the influence of pressure and temperature on the measured CPD. In the first set, the measurements was commenced under

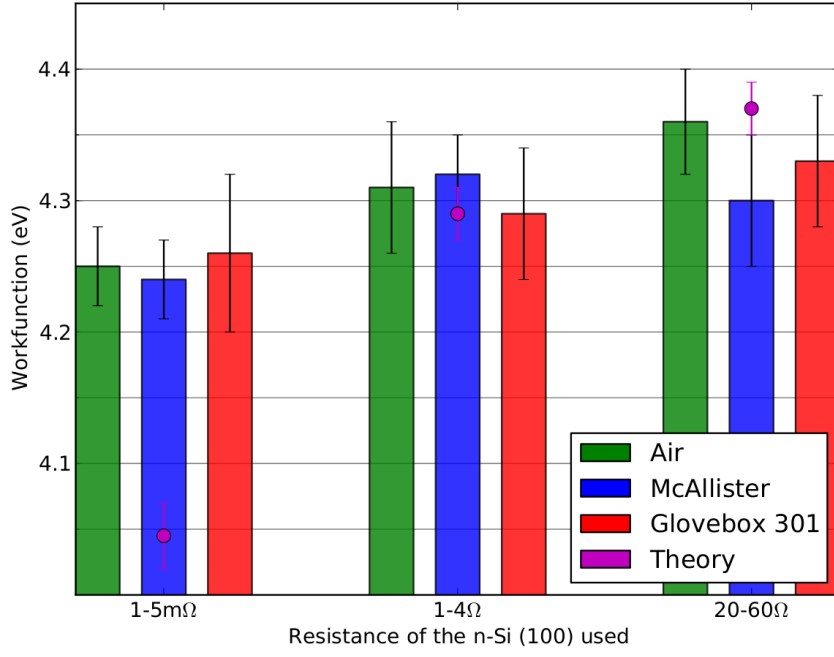


Figure 5: Summary of the calculated work functions for the n-Si-H samples used. There is good agreement between the different systems and good agreement with theory, except for the case of low resistivity, highly doped silicon. Indicated errors include deviations in the samples & the inaccuracy of calibration with HOPG.

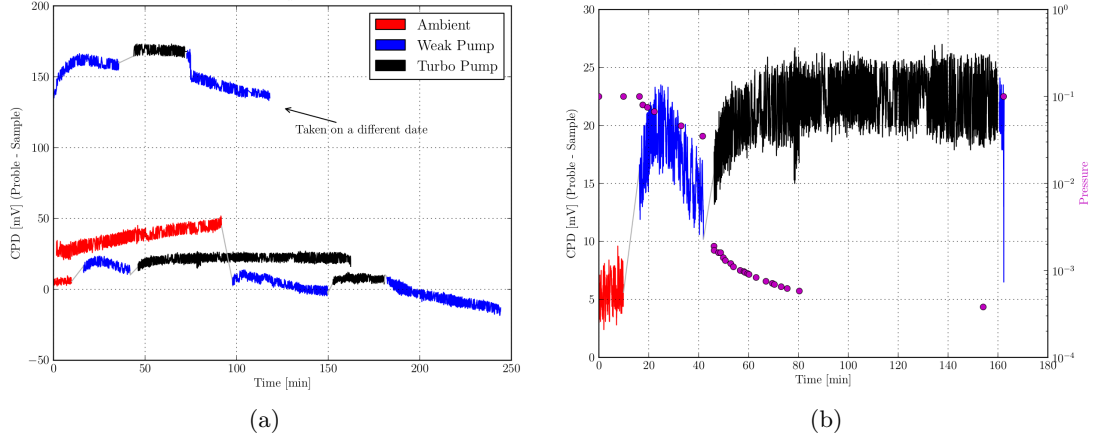


Figure 6: Bla

ambient condition and allowed to continue for some time. The probe head was then retracted to avoid crashing it onto the sample and the weak pump was turned on. The probe head was then brought into proximity of the sample to continue the measurement and the measurement was allowed to continue for some time. The probe head was retracted again and the turbo pump was switched on. Again, the probe head was lowered to continue with the measurement and the measurement was allowed to continue for some time. For results of this experiment, see Figure 5.1. This experiment revealed several features. Firstly, the CPD of HOPG rises as a function of time under ambient condition. This is readily explained by oxygenation and/or other sources of contamination from ambient, such as water for example. Once the weak pump is turned on, there is a discontinuity in CPD. This discontinuity is not systematic in its direction, it may change the CPD either 'up' or 'down' and can therefore best be explained by a displacement of the probe head over the sample. The sudden reduction in pressure exerts a force on the probe arm and may cause it to move slightly. The size of the discontinuity is within the size of variation of CPD observed when different spots of the same reference are measured. The CPD now reduces as a function of time and this may be explained by gradual decontamination of the sample: as the pressure reduces, previously adsorbed contaminants may leave the surface. A second viable explanation may be a gradual change in acoustic vibration characteristics as a result of the reduction in pressure. To distinguish between the two, an experiment was performed in which the sample chamber was flushed with clean, inert Argon after having been subjected UHV conditions for about 20 minutes. It is assumed that complete desorption of possible contaminants is achieved by this treatment and that the high purity argon does not introduce fresh contaminants. The pressure was then again reduced using the weak pump and the CPD again reduces as a function of time. We therefore conclude that the observed reduction in CPD is indeed caused by gradual changes in pressure rather than desorption of contaminants. It is thus advisable to carry out CPD experiments under conditions of stable pressure, especially given the fact that the probe head is specifically designed by Mc Allister to carry out ultra-high vacuum CPD measurements.

5.2 CPD as a function of temperature

To determine the possible influence of temperature on the quality and reliability of the measurement, an ultra-thin layer of aluminium was deposited onto a piece of silicon by atomic-layer-deposition and a natural layer of surface oxide was formed. Alumina was chosen as a surface

of interest because of its natural affinity for water. If contamination by water and subsequent freezing of the surface is an inherent problem of low temperature CPD measurements, then a strongly hydrophilic surface should exhibit these problems. A fresh wafer of silicon with 20 nm of aluminium by ALD was cut into suitable pieces. Pieces were swiped off with ethyl-acetate and sonicated for three minutes in iso-propanol, blow-dried under N_2 and subsequently microwave-treated in an O_2 -plasma at 100W with a flow of $1\text{cm}^3/\text{min}O_2$ and $1.5\text{cm}^3/\text{min}Ar$ for 3 minutes, ensuring a clean alumina surface. The back-side was scratched and InGa-eutectic was applied to create a back-contact. The work-function of this surface was measured in the ambient probe station and found to be 4.0 ± 0.12 eV. To ensure an ohmic back-contact, the sample stage of the Lakeshore was lightly scratched and a small quantity of InGa-eutectic was applied to the stage. The piece was then placed on the sample stage and slight pressure was applied. The stage was introduced into the Lakeshore cryogenic system and the pressure was reduced. Using liquid nitrogen and the heaters, the temperature was reduced to 250 K and allowed to stabilise. Under these conditions, the work-function of the alumina surface was found to be 4.17 ± 0.15 eV⁵. It has to be pointed out that the sample surface is not the coldest point inside the Lakeshore's inner chamber. Because of the way liquid nitrogen is introduced into the system, the radiation chamber's ground surface is the coldest. Therefore, it can be assumed that any ice would form there rather than on the sample, corroborating the result presented above.

5.3 Conclusion

CPD measurements using the Lakeshore are feasible when the pressure is constant. They may be carried out under ambient pressure with an inert argon atmosphere or under ultra-high vacuum conditions. A changing pressure is not conducive for reliable measurements of the contact potential difference but under conditions of stable pressure, CPD values obtained from the Lakeshore agree with values obtained from the other probe stations. Lowering the temperature below the freezing point of water does not pose an inherent restriction on the feasibility of CPD measurements in the Lakeshore system. The observed CPD was in agreement with experiments carried out at room temperature. In agreement with the literature [1, 2, 3, 4, 5] possible fluctuations of the work function of the probe head are small compared to other sources of experimental uncertainty and the WF can indeed be taken as a constant.

6 Measuring the SPV at room temperature

A necessary condition for the successful determination of the SPV of a sample is saturation with light. In practice, this means that the light-intensity during a measurement of the SPV is gradually increased up to the point where further increase in intensity does not lead to further increase of the measured surface photovoltage. Detailed interpretation of the measured signal is often problematic and requires intimate knowledge of the sample and even theoretical discussions of the SPV tend to be very involved. However, from the point of view of establishing whether a new experimental set-up is suitable for more advanced SPV-measurements, a successful, saturated measurement of the SPV of a relatively simple test-sample is a necessary precondition. To that end, SPV measurements of an alumina surface were chosen as a test case. Alumina was chosen for its stability, relative simplicity and because of its relatively large SPV signal. The sample is the same as used for the determination of the temperature dependence of the CPD: 20 nm aluminium deposited by ALD onto a wafer of silicon. The preparation and cleaning protocol of the sample is

⁵A suitable piece of HOPG was also present in the sample chamber to allow for calibration of the work-function of the probe head

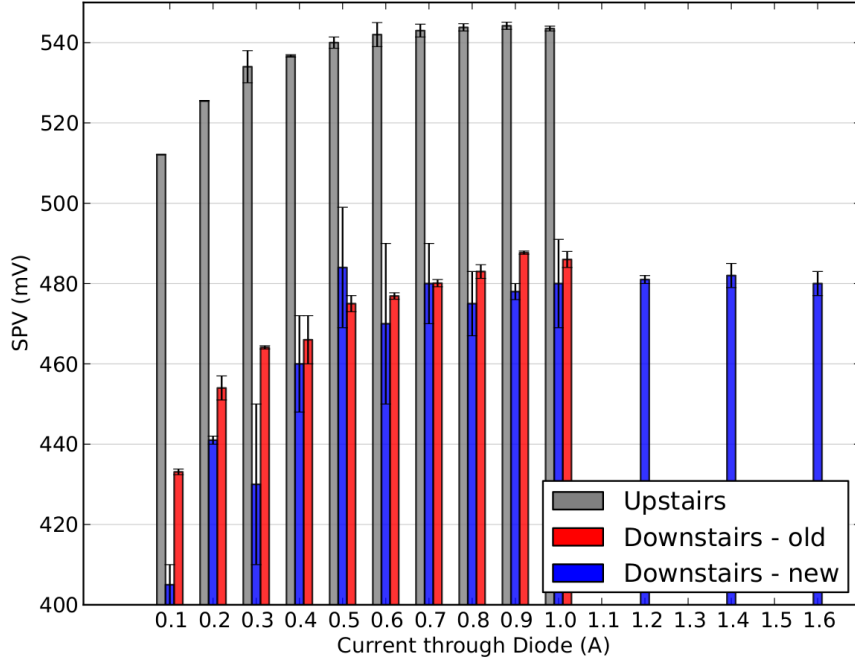


Figure 7: Bla.

the same as above: rinsing; sonication; oxidation and creation of an ohmic back-contact using InGa-eutectic. The sample's SPV was determined in the ambient probe station as is ⁶ and was found to be 530 pm 20 mV. To check if the LED is a suitable source, it was installed in the ambient probe station and an SPV measurement was carried out. To facilitate the comparison between the systems, the ambient probe station's light focusing lens was removed as no such lens could readily be installed with the Lakeshore. Since the LED has a variable electrical source, it was possible to increase the current through the LED from 0 to 1 A in steps of 0.1 A. The sample was then introduced into the Lakeshore's inner chamber and the LED was placed on top of the vacuum chamber's outer window. The current through the LED was increased in the same steps as for the measurement in ambient and the results of the experiment are summarised in Figure 7. In that Figure 'Upstairs' refers to the measurement in the ambient probe station, 'Downstairs' refers to the measurement with the Mc Allister probe head, 'old' refers to the initial LED with only 12 of 25 spots working and 'new' refers to the newly purchased LED in which all diodes are working and which achieves a maximum illumination of 5200 lm. It has to be pointed out that the new LED could be driven further than up to a maximum of 1.0 A to reach its full illumination intensity at a maximum current of 1.6 A, so the experiment was extended to make use of the maximum achievable intensity. As can be seen, saturation of the SPV is readily achieved with the LED in ambient at a current of 0.6 A and the measured value of 540 pm 10 mV is in good agreement with the value expected from the measurement of the SPV with a xenon light source. It is furthermore apparent that the measurement achieves saturation. At a current of about 0.8 A, a further increase in current does not result in a corresponding significant increase in measured surface photovoltage. However, there is a significant discrepancy of 60 mV ⁷ in measured SPV

⁶i.e. ambient probe station and xenon light source

⁷about 10% of the maximum signal

between the two systems which cannot readily be explained. A similar experiment using neutral density filters to control the light intensity was carried out, but no meaningful conclusions could be drawn from the results, so it is not presented here. In a following step, the SPV of the alumina sample was measured with the Lakeshore not completely assembled. The vacuum chamber's lid as well as the radiations shielding chamber's lid were removed and the LED was held by hand as close to the probe head as possible without interfering with the measurement⁸. This configuration obviously does not represent a working condition for the Lakeshore, nor is it readily reproducible because of its vague parameters, but an SPV of ~ 480 mV could be achieved in this way. At this point, the nature of the 60 mV discrepancy remains unknown. It might be due to the increased distance between the source and the sample or it might be due to partial absorption by the Lakeshore's windows, especially the IR-shielding sapphire glass but the results obtained here remain hard to interpret properly. Saturation is achieved, but not at the right level. Simply using a stronger source will therefore most likely not alleviate the problem. It may be tried to replace the windows by lenses which better focus the light beam onto the sample but is is questionable if such a scheme is practically feasible or indeed even helpful. Practically, such window-lenses would have to be able to withstand UHV conditions and saturation was achieved in ambient even without a lens, where the distance between sample and source is comparable to the corresponding distance in the cryogenic system. Since no explanations of the source of the discrepancy between the systems are forthcoming, a systematic experimental uncertainty of underestimating the SPV by about 10% has to be assumed when using the Lakeshore in conjunction with the LED.

7 Temperature dependent measurement of the SPV

Since it was established that temperature dependent CPD measurements could reliably be carried out and that, albeit with a systematic uncertainty, SPV measurements could also be carried out with the Lakeshore cryogenic system, the final step was to attempt a combined experiment and carry out a temperature dependent measurement of the surface photovoltage. To this end, a suitable sample needed to be identified. This sample should have a sufficiently large photo-response and should undergo some phase transition at a well defined, critical temperature. Three different systems were investigated: biological samples consisting of a plant's photo-system immobilized on a gold surface; a lead-iodide-chloride perovskite on titanium-dioxide and finally a thin layer of vanadium oxide.

The biological samples exhibited changes in CPD on the order of 20 mV. These changes occurred at a well defined temperature, between 250 and 260 K. While interesting, these changes but were too small to serve as a reliable system for a proof of principle: 20 mV is within the experimental uncertainty of both the CPD and the SPV measurements. The biological samples were therefore quickly abandoned.

For the perovskites, it was attempted to compare their reaction when exposed to different parts of the optical spectrum, namely to compare their dark CPD to the CPD when exposed to full spectrum illumination and when exclusively exposed to infra-red illumination. The perovskite sample was introduced to the inner chamber of the Lakeshore and electrically contacted with the help of a conductive clip and screw. To allow for electrical connection via the back contact, the perovskite was removed from the point where the clip contacted the sample. The cryogenic system was evacuated and seven temperatures were chosen at which to measure the CPD: 130, 170, 210, 230, 250, 270 & 280 K. At each of these temperatures, the dark CPD was measured. A filter which would only allow IR radiation to pass was placed in front of the source, the sample was briefly illuminated and the IR CPD was measured. The CPD of the system was allowed to

⁸a constant stream of argon was employed to avoid undue contamination of the inner chamber from ambient.

decay back to its original dark value and the filter was removed. The system was then briefly illuminated by full spectrum at high intensity and the light CPD was measured. The CPD of the system was allowed to decay back to its original dark-value and the system was then cooled down to the next temperature step. In the course of this measurement, repositioning the probe head to new positions over the sample was necessary because although care was taken, crashing the probe head onto the sample could not be avoided. The whole experiment was carried out under low pressure conditions, but for the lowest five temperature points, the pressure was about a factor ten lower than for the measurements taken at 270 & 280 K. For the sake of completeness, the results of this measurement are shown in Figure ?? and briefly summarised here. The light CPD varies over a range of ~ 100 mV. The difference between dark and light CPD, i.e. the light SPV ranges from approximately 200 to approximately 350 mV. The IR CPD varies over a range of about 300 mV and the IR SPV varies both in magnitude as well as direction: from approximately 80 to about -220 mV. None of these parameters show a clear dependence on temperature in their variation. To carry out the experiment, the set up of the Mc Allister had to be modified twofold. Measurements had to be carried out without the inner chamber's sapphire glass window as this would exclude any infra-red radiation from reaching the samples in the first place. Secondly, the xenon lamp had to be used as a source of illumination to give access to the infra-red part of the spectrum. These modifications introduced experimental difficulties for several reasons. As already pointed out, the xenon lamp is a source of heat and therefore, an unknown experimental uncertainty in the temperature was introduced. The experiment had to be carried out very quickly to avoid damage to the system and to minimize said uncertainty in temperature. In effect, only a brief flash of illumination could be allowed to reach the sample. Furthermore, the xenon lamp and its high power electrical source had to be set up in close proximity to the Lakeshore cryogenic system and electrical noise due to the relatively high currents and voltages involved in this experiment were introduced. To add to these problems, the sample was neither fresh nor necessarily stable and perovskites are inherently complicated systems so it was decided that this experiment could not serve for the purpose of showing a reliable SPV(T) measurement.

7.1 Vanadium oxide

7.1.1 Discription of samples and preliminary research carried out at the Cahen group

Vanadium-dioxide (VO_2) is a system well known for undergoing a metal to insulator transition (*MIT*) close to room temperature. At the heart of this transition lies a reconfiguration of the of the crystal lattice, where VO_2 transitions from its high-temperature tetragonal (rutile) phase to a low temperature monoclinic phase. In the tetragonal phase, the Fermi level of the material is well within the conduction band and hence, the material behaves like a metal. In the monoclinic phase, an energy gap has developed and the material now behaves like an insulator [12]. Of course, the only difference between an insulator and a semiconductor is the size of their energy gaps and if the transition occurs gradually, one might also speak of a metal-semiconductor-insulator transition instead of an *MIT*. This transitions has extensively been studied, using many different methods such as direct photoemission & x-ray absorption spectroscopy [13], Raman spectroscopy [14], ultra-fast pump-probe spectroscopy [15] etc. However, because of their relative simplicity, studies of the resistivity of the material stick out [16]. In these, changes of resistivity over several orders of magnitude are not uncommon. Finally, the MIT in VO_2 was also investigated using Scanning Kelvin Probe Microscopy, where ~ 200 nm thin stripes of the material were grown adjacent to a stripe of gold (*Au*). These strips were continuously scanned over a temperature range including the phase transition temperature (T_{MI}) of VO_2 . *Au* provided a stable reference work function

and thus, the work function of VO_2 could be measured in absolute terms. It was found that vanadium-dioxide has a work function of ~ 5.15 eV in its metallic phase and that the work function gradually decreased by ~ 0.15 eV over a range of 60 K [17]. In other studies [18], it was found that MIT could be tuned by tungsten-doping of a thin film of VO_2 grown on a supporting matrix of TiO_2 and preliminary research into similar samples has already been carried out in the Cahen group.

The samples were either pure or 2% tungsten-doped vanadium-dioxide of thickness ranging from 10 to 80 nm grown on either TiO_2 or on niobium-doped titanium-dioxide ($Nb : TiO_2$) and were kindly provided by M. Nakano of RKIEN. A change in resistivity of several orders of magnitude upon MIT could be shown for these samples. When used for this project, however, the collection of vanadium-dioxide samples had already been in storage inside a desiccator for more than a year. Many samples were damaged and proper storage throughout the year could not be guaranteed. Therefore, the choice of sample for this project was limited to pieces which, upon optical inspection, were closest to their initial appearance and were still large enough to allow proper positioning of the probe head over a sufficiently homogeneous surface. Therefore, a sample of 50 nm 2% $W : VO_2$ on pure TiO_2 was chosen. It had been investigated by Nir Kedem using the van der Pauw method with a temperature resolution < 5 K. It showed an approximately two orders of magnitude change in resistivity with a relatively gradual profile, occurring over the temperature range from 220 to 270 K. The resistivity also exhibited hysteresis, with up to half an order of magnitude difference in resistivity between cooling down and heating up.

7.1.2 Experimental procedure, results and discussion

Initially, the work function of the vanadium-dioxide sample was determined with the ambient probe station. The sample was sonicated for three minutes each in acetone, ethanol and THF and was then blow-dried under N_2 . To calibrate the probe head, a fresh surface of HOPG was prepared and the CPD was measured. The work function of the probe head was found to be 5.085 ± 0.15 eV. The work function of the clean $W : VO_2$ sample was determined to be 5.17 ± 0.20 eV, in remarkable agreement with the value obtained by Ko et al. [17].

Before each measurement, the sample was subjected to the same cleaning procedure outlined above. The sample was then blow-dried under N_2 and placed directly on the ground of the inner chamber of the Lakeshore. Electrical contact was made from the top using a conductive screw and clip. The Lakeshore was then evacuated and the experiment commenced once a stable vacuum condition was obtained.

In the first experiment, the Lakeshore was cooled down to the lowest temperature achievable by liquid nitrogen cooling: 97 K for this cryogenic system. During this cool-down, the CPD was quickly measured at three points where the temperature remained relatively stable for a sufficient time. Once the lowest possible temperature was reached, the flow of nitrogen was stopped, the heater was set to 300 K and the CPD was measured continuously. This protocol allows for a quick measurement of the CPD(T)-response of the system to identify the temperature range of interest, but uncertainties in temperature are introduced because of the temperature gradient present in the inner chamber and because of having to note down the temperature manually. The experiment had to be aborted. The data obtained during this initial experiment are shown in Figure 8.

For the next experiment, the temperature range was extended and more care was taken to more accurately determine the temperature. The system was cooled down to 100 K and gradually increased. The CPD was measured at 11 well defined temperatures. For each of these temperatures, the flow of liquid nitrogen and the heater setting were carefully adjusted until all three of the cryogenic system's temperature read-outs were within a range of 5 K of each other.

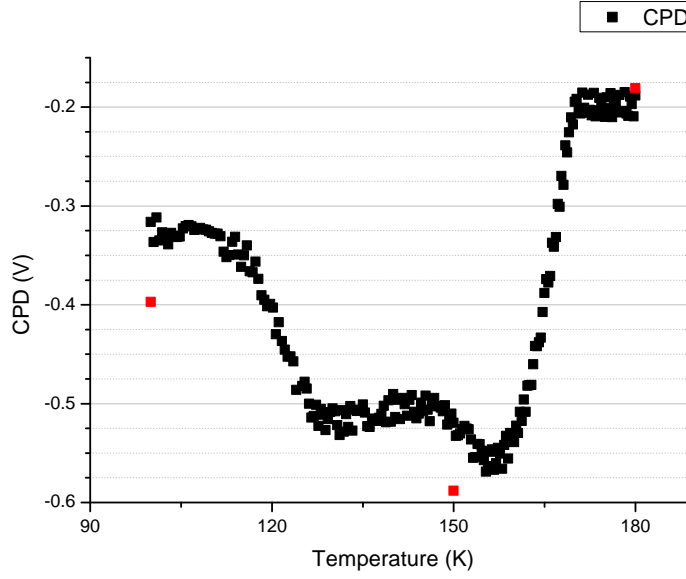


Figure 8: Raw data of the contact potential difference of the $W : VO_2$ obtained during a temperature-sweep. Data points in red were obtained while cooling down, data points in black were recorded while warming up.

Holding the temperature constant, the CPD was then recorded once every second for a period of 100 seconds and these data were averaged. The temperature was increased to the next set-point and the procedure was repeated. The observations of this experiment are plotted in Figure 9. The uncertainty in CPD was taken to be twice the standard deviation of CPD values obtained during the 100 second period. Uncertainty in temperature is not shown but assumed to be less than 5 K.

In the last experiment, both dark and light CPD were measured for the same sample for a range of temperatures between 180 and 300 K in intervals of 20 K. CPD was only measured once the temperature gradient inside the Lakeshore was less than 5 K. For each temperature, dark CPD was measured once every second over a period of 100 seconds and these data were averaged. Illumination for light CPD was achieved by the LED at maximum intensity and to avoid possibly heating the sample, light CPD was measured for 15 seconds. HOPG as a reference for the work function was not used in this experiment. Instead, the work function of the sample at 300 K in vacuum was assumed to be the same as that obtained from the same sample at room temperature in ambient and the work function of the probe could therefore be calculated to be 4.41 eV. The results of this final experiment are shown in Figure 10. The experimental uncertainty in work function includes twice the standard deviation of dark CPD obtained during the 100 second interval plus an added uncertainty from the calculation of the work function of the probe head. The experimental uncertainty in SPV includes uncertainty from dark CPD as well as that for light CPD. Uncertainty in temperature is, again, not shown, but assumed less than 5 K.

Probably the most remarkable feature of these measurements is the sudden drop in CPD (sudden rise in WF) at ~ 120 K and the consequent sudden rise in CPD around ~ 170 K seen in both Figure 8 and Figure 9. Since these features were observed during cool down as well as during heating up in the first and were again observed in the second, independent measurement, they are

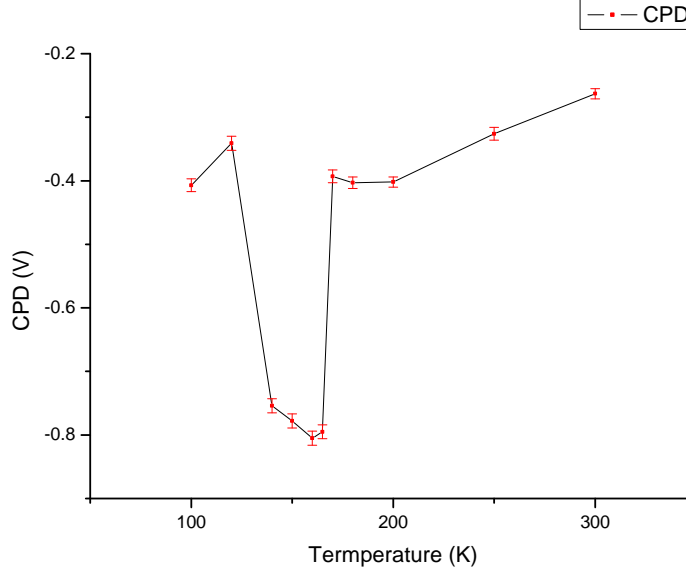


Figure 9: The contact potential difference of the $W : VO_2$ sample as a function of temperature. Experimental uncertainties are explained in the text.

most likely not an artefact of the measurement, nor should they be ascribed to simple experimental failure. They represent a change in work function of ~ 200 to ~ 400 meV which is remarkably large. Such changes can most likely not be explained by changes in shielding of accumulated surface-charges or repositioning of the Fermi level. A (reversible) surface-reconstruction or even a (reversible) change of chemical composition might be able to explain the data, but without further measurements, we cannot be sure. To the best of my knowledge, neither a structural reconstruction nor a change in WF at the temperatures in question has yet been reported in the literature for $W : VO_2$. In conjunction with the measurements carried out by Nir Kedem, the experiments reported in the literature and those summarised in Figure 10, it has to be assumed that the changes in WF seen at around 120 & 170 K are not explained by the known *MIT* of vanadium-dioxide. The difference in CPD between heating up and cooling down seen in Figure 8 might be taken as evidence for hysteresis at lower temperatures than previously observed, but the data is sparse, so no conclusive explanation can be drawn from them. Figure 9 on the whole corroborates what was observed in the initial, relatively inaccurate experiment even though the size of the observed effect is greater, but nothing more can be concluded from these measurements alone.

We will now concentrate on the measurement of the SPV as shown in Figure 10. A significant SPV is observed below 280 K, at 240 K the SPV is at its maximum of ~ 120 mV and below 220 K SPV is reduced back to levels comparable to those at room temperature. A significant SPV signal is therefore observed in the same temperature range that was identified for *MIT* in the resistivity measurements. In the metallic rutile configuration, no SPV is observed and none is expected. As the energy gap of the material gradually widens, the SPV gradually increases because gradually less thermally free carriers can shield trapped surface charges in the dark condition. The simultaneous presence of both phases of vanadium-dioxide over a range of temperatures has been observed in the literature [19]. As a result, band bending and hence observed SPV

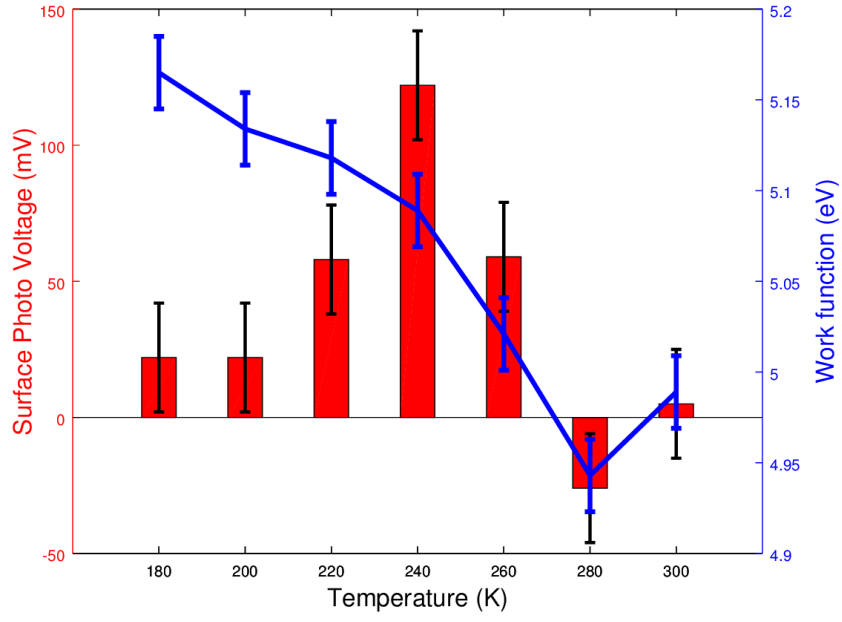


Figure 10: Measured surface photovoltage and calculated work function for the $W : VO_2$ sample as a function of temperature. The appearance of an SPV coincides with the *MIT* temperatures observed in earlier measurements, its positive sign indicates an n-type semiconductor. The change in WF is substantial but remains unexplained without further experiments. Experimental uncertainties are explained in the text.

gradually increase. If the SPV is assumed to be saturated at 240 K and, accordingly, the bands to be flattened, the band bending is ~ 120 meV. Possible Fermi level pinning would add to the size of the band bending, so the stated value has to be seen as a minimum. On first sight, the gradual decrease in SPV signal might be puzzling. One would expect the trend for the SPV to continue, after all, the idea behind low temperature SPV is to counteract thermally free carriers and increase the influence of electron-hole pairs created by absorption of light. However, the observation made here can be explained if one recalls that vanadium-dioxide is undergoing a metal to *insulator* transition and that for an insulator, the energy gap is expected to be relatively large. Looking at the spectrum of illumination, Figure 4, a clear cut off below 400 nm is seen. 400 nm radiation corresponds to a photon energy of ~ 3.1 eV so if the energy gap in VO_2 becomes larger than this, no carriers can be created by illumination or rather: only a minute fraction of incident photons corresponding to the minute fraction of photons at the low-wavelength tail of the LED will have sufficient energy to create free carriers. Therefore, the sample is no longer saturated by illumination and a significant drop in observed SPV signal is expected. A problem with that interpretation is that the band gap of vanadium-dioxide is consistently reported as ~ 0.7 eV, from theoretical [20] as well as from experimental studies [21, 15, 13, 22]. Concentrating on the temperature range 180 to 300 K, a change in WF of ~ 150 meV is seen in both in Figure 9 and, more clearly, in Figure 10. So far, positive changes of WF of up to 450 meV have been observed for bundlelike VO_2 nanostructures [23]. A change of ~ 150 meV was also reported by Ko [17] during the *MIT* of vanadium-dioxide, but they observed a decrease instead of the increase in WF seen here. The difference between the sample used in their research and the one used here is the presence of tungsten as dopant. Tungsten has more valence electrons than vanadium even in its elemental state and certainly has more valence electrons than vanadium in its oxide. Tungsten should therefore act as n-type dopant. This is in accordance with the sign of SPV observed in Figure 10. The change in WF can not be explained by a gradual change in the position of the Fermi level: for an n-type material, E_f is expected to increase with lowering temperature. The carrier concentrations inside the material might change drastically due to dopant freeze-out or other mechanism and that might change E_f sufficiently to account for the rise in WF, but without further experiments, these attempted explanations remain speculative. In fact, there is doubt in the literature if a simple ‘gap opening process’ can indeed explain the observed *MIT* [24, 25]. Judging by the complexity of the material, attempts at explaining the observed data in terms of simple band diagram considerations of typical metals and n-type semiconductors will fall short. Similar experiments with an extended spectral range or a more detailed study of spectral surface photovoltage might serve to verify the results obtained for this material here, but they are out of scope of this project: elucidating the finer details of the *MIT* observed in $W : VO_2$ was not the aim of this project. Vanadium-dioxide was, above all, chosen as a system to show a viable SPV(T) measurement, to serve as a proof of concept for measuring temperature dependent SPV with the Lakeshore cryogenic system. This was achieved with these experiments.

8 Conclusion

A series of experiments showed the viability of using the Lakeshore cryogenic system equipped with a Mc Allister Kelvin probe head and an LED illumination source as a system to measure temperature dependent changes in the surface photovoltage. To do so, the CPD obtained under various circumstances, namely in ambient, under low pressure and at temperatures below freezing was compared to existing, trusted systems. Deviations between the systems were within normal, acceptable experimental uncertainties usually encountered when using Kelvin Probe measurements.

The SPV obtained from measurements in the Lakeshore at room temperature was shown to agree with SPV measurements carried out in the ambient system and lastly, experiments to show a viable SPV(T) measurement were carried out. Some aspects of these experiments were shown to be in good agreement with earlier, preliminary research carried out in the Cahen group and with results reported in the literature while the finer detail and precise interpretation of all the observed features remains elusive without further investigations. However, with vanadium-dioxide, it could be shown that interesting and reproducible data can be obtained by using the Lakeshore cryogenic system for CPD(T) and SPV(T) measurements.

9 Appendix

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