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Measuring the behaviour and properties of carriers in a Silicone probe

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This report aims to investigate the behaviour of carriers in a superconductor following controlled carrier injection. To achieve this goal, a silicone probe was utilized to evaluate the behaviours of carriers that experienced voltage injections. The properties of this electrical input were modified during the testing process, which allowed for the establishment of experimental relationships between the carriers' behaviours and their causes. Specifically, the study focused on carrier mobility, which was determined to be 103.3 ± 4.6 cm^2/Vs, and the diffusion coefficient, which was found to be 2.89 ± 0.85 cm^2/s. These results provide insight into how carrier properties and behaviour could showcase macro-properties of the superconductor, such as temperature or the purity of the doping levels of the probe.

I. INTRODUCTION

In 1948, J.R. Haynes and W. Shockley conducted the Haynes-Shockley experiment [4], which demonstrated that the diffusion of minority carriers in a semiconductor could result in a current. This led to the invention of the point-contact transistor, which revolutionized the field of electronics and enabled the miniaturization of electronic circuits. Today, transistors are present in nearly all electronic devices, including computers, smartphones, and home appliances.

The properties and behaviours of carriers in semiconductors play a vital role in transistor physics. To better understand these properties, this report presents a comprehensive review of carrier properties and recombination effects due to state excitation. Direct measurements of drift mobility, diffusion coefficient, and recombination lifetimes of excess carriers in semiconductors are compared to existing solid state physics models. The report aims to test the properties of carriers in a semiconductor against predicted values and to add to the existing body of research on this topic.

II. THEORY

Semiconductors are materials which have electrical conductivities intermediate between those of good conductors and good insulators, due to having a relatively small energy gap between the filled valence band and the empty conduction band of their electrons [1]. When electrons in semiconductors are excited with sufficient energy, they can move from the valence band to the conduction band. To respect energy and momentum conservation, these electrons leave behind a vacancy, commonly known as "hole" in the valence band. This move is illustrated in Figure 1. Holes behave as positive carriers and can move in accordance to the applied electric field.

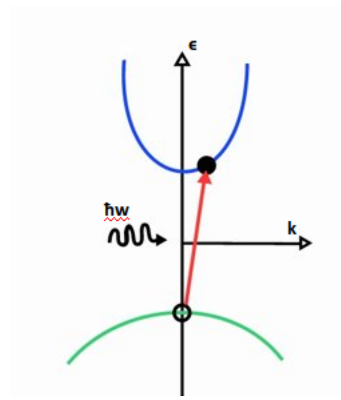

FIG. 1: Theoretical representation of the excitation of an electron from the valence band to the conduction band in a direct band gap semiconductor (does not require a phonon for energy and momentum conservation) and the appearance of a hole in its place. - CHANGE SEE PICS

The velocity of carriers (holes and electrons) can be evaluated by the following equation:

$$\frac{1}{2}mv_{th}^2 = \frac{3kT}{2} \tag{1}$$

$$\therefore v_{th} = \sqrt{\frac{3kT}{m}} \tag{2}$$

In addition to velocity, carriers also have a defined mobility. Carrier mobility refers to the ease with which charged particles can move through a material in response to an electric field, it is affected by factors such as the material's crystal structure, dopant concentration, and temperature. It is defined as:

$$\mu = \frac{q\tau}{m^*} \tag{3}$$

with μ corresponding to the carrier mobility, q corresponding to the charge of the carrier, τ corresponding to the carrier relaxation time, also known as the scattering time of the evaluated carriers, and m^* being the effective mass of the carrier.

The relation between carrier mobility and the properties (specifically impurities) of a material was first demonstrated in the 1950 Haynes-Shockley experiment [3], which was partially reproduced as a part of this larger study on superconductor carriers. The experiment involved measuring the resistance of a thin slice of germanium at different temperatures and doping concentrations. These results showcased an increase of the material's impurities associated with a decrease of the germanium's resistance, indicating an increase in conductivity. The experiment also revealed that the mobility of electrons decreased as the doping concentration increased. Although utilizing a different superconducting material and a different experimental setup from the original experiment, it is important to note that this study builds on this previous discovery and attempts to showcase its proven results in a different setting as well as expand on the study of carrier properties beyond the original experiment's scope.

Part of this expansion has looked into the diffusion of carriers after a carrier injection in a superconductor. The diffusion coefficient of carriers, defined by:

$$t_p = \frac{WL}{\mu V} \tag{4}$$

has been key to the performed analysis. In Equation 4 W corresponds to the spatial width of the hole pulse in the sample (measured at half peak amplitude) at time t given by:

$$W = \sqrt{16ln(2)D_h t} \tag{5}$$

with D_h being the diffusion constant for holes in n-type material. Einstein's relationship for a semiconductor:

$$T = \frac{Dq}{k\mu} \tag{6}$$

is also utilized in this report to study the correlation between obtained values for diffusion and mobility and the expected superconductor temperature.

III. EXPERIMENTAL

Through most of this experiment, the apparatus was set up as shown in Figure 2. A function generator was set to generate pulse cycles which were delivered to a pure silicon probe. Each pulse had a measured frequency of 1 kHz, with a maximum voltage of 10V and a burst period of 6 μs. These initial values were set as a starting point for the experiment, and were modified throughout the various tests. These specific starting values were chosen as they were of reasonable magnitude and length.

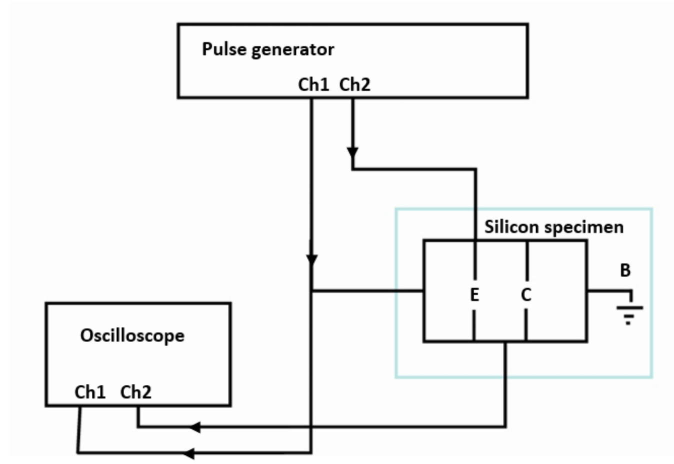

FIG. 2: Schematic diagram of the experimental circuit set-up used. The pulse generator is connected to a silicon specimen which will serve as our superconducting probe through the experiment. An oscilloscope is then attached to the silicon specimen to observe the effects of pulse injections in the material.

Through this experiment the drift velocity, mobility, thermal velocity, mean free hole time scatter, carrier diffusion, hole pulse broadening, field reversing and effects of distance when detecting carrier movements were tested. Most of these tests simply required a modification to the initial pulse cycle generation properties, but for the purpose of testing how the distance from the silicon specimen to the collector might affect the results, it is important to understand the architecture of our silicon specimen setup. This setup is illustrated in Figure 3, and showcases a separation of 75 μm between each of the four collectors and a separation of 225 μm from our probe to our first collector. The distance between these collectors allows us to better observe the evolution of the carrier injection across the available distance and by distances' relation to time. Unless specified otherwise, all the discussed data in this report was obtained from collector 1.

It is important to note that when outputting a field voltage of 6V with our function generator, the obtained voltage using an oscilloscope was measured at 100mV. Although this is a considerable loss of voltage through the system, it does correspond with resulting oscilloscope readings and therefore has been accounted for in the data and graph mentions of input voltage. This loss is most likely due to noise and attenuation caused by the experimental set-up.

IV. RESULTS AND SPECIFIC DISCUSSION

The presence of carriers in the semiconductor can be observed after an injection of voltage into the system. As seen in Figure 4 after a short pulse of current is ap-

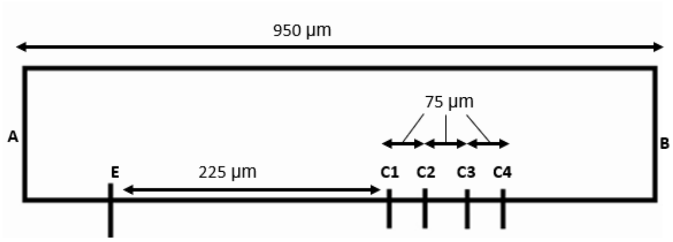

FIG. 3: Schematic diagram of the experimental silicon specimen setup used. To the sides of the set-up the letters A and B showcase the position of the setup with respect to the larger experiment with side B corresponding to the ground connection. As shown in the image, there are 4 available collectors within our setup that are all separated by 75 μm between each other, in addition to a 225 μm separation from the probe. The complete setup has a length of 950 μm. In this case, the letter E correspond to the Chanel 2 connection from the pulse generator as seen in Figure 2 and thus to the location of our silicon probe.

plied to our superconductor probe, we observe a following Gaussian shape, and finally a negative spike equivalent to the original injection. The time of transit of this pulse is measured from the injection spike until the maxima of our Gaussian distribution. This Gaussian distribution showcases the rise and decay of the excitation of the pre-existing carriers (electrons) in the material. During the first half of the Gaussian these electrons experience excitation due to the injected pulse, but after the maxima is reached this excitation begins to decay until the superconductor returns to its previous state after the carriers dissipate. This return to its normal state creates an opposite transient voltage, which corresponds to the observed negative spike.

A. Carrier properties

The transit time of the carrier injection through the material was evaluated by comparing the obtained outputs with different pulse amplitudes. Figure 5 illustrates a superposition of the results obtained by these inputs and showcases the "loss" of that Gaussian shape as the voltage of the injected pulse is reduced and thus so are the number of excited carriers.

This same effect is observed when modifying the pulse length. Longer duration pulses result in a more gradual build-up and decay of the excitation, which leads to a more Gaussian shape. You can see this effect in Figure 6.

The Gaussian shape is consistent with Drude's theory predictions, which claim that electrons in a conductor act as classical ideal gas. This gas like diffusion goes from high to low concentration with a Gaussian distribution that can be modelled as a one dimensional random

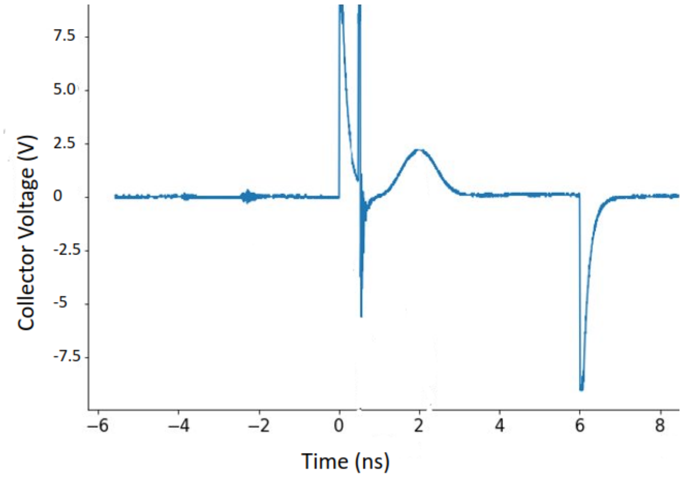

FIG. 4: Obtained voltage output when running the standard experimental setup as described in section II. One can observe the initial carrier injection at time 0, followed by a Gaussian distribution observed between 0.5 ns and 3 ns, and finally a negative spike opposing the injected voltage spike.

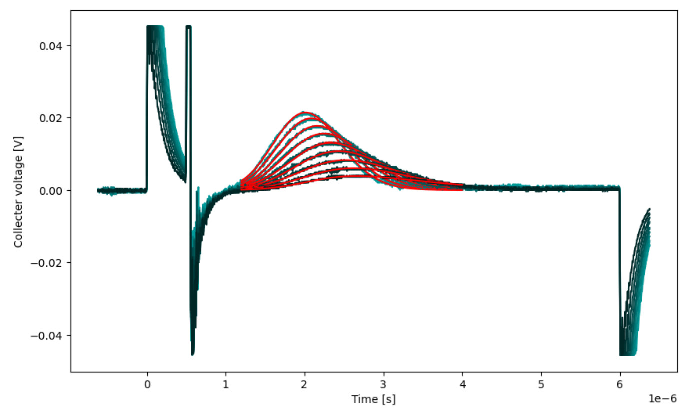

FIG. 5: REDO THIS - NOT CUT AT THE TOP + MORE VISIBLE SCALE + MAKE SURE VOLTAGE IS CONSISTENT ACROSS ALL DATA

walk[1]. Figure 9 illustrates the results of our random walk simulation, which are consistent with theoretical predictions and experimental results, therefore solidifying our argument.

B. Carrier diffusion

Evaluating field voltage against inverse transit time allows us to obtain the carrier's drift velocity. Figure 7 showcases the obtained field voltage against inverse transit time obtained results.

– FINISH THIS REASONING ON DRIFT VELOCITY

When evaluating the experimental set-up across col-

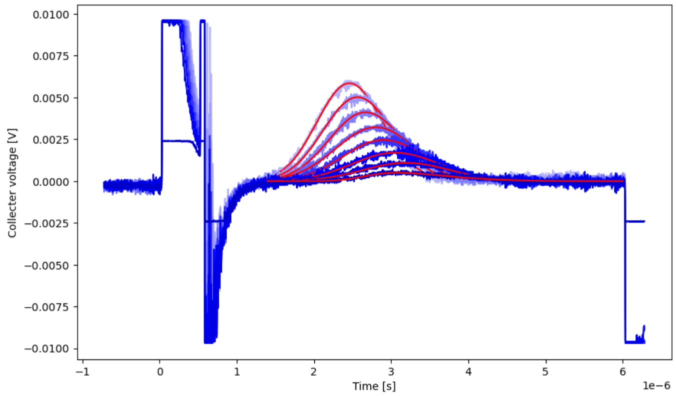

FIG. 6: REDO THIS - CHANGE COLOUR & EXPLAIN BETTER W.R.T FIG 5 (longer pulse) - maybe get one with same V

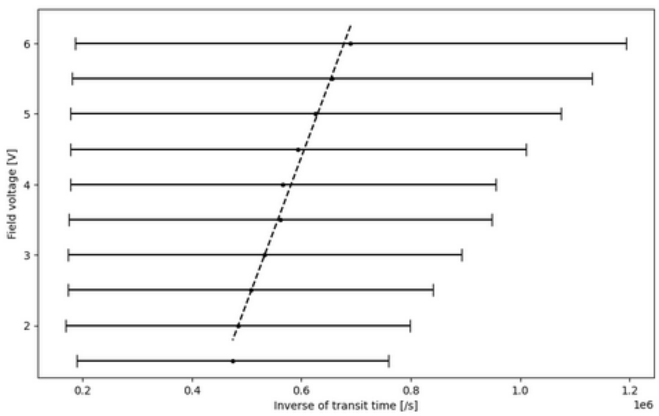

FIG. 7: Field voltage against inverse transit time plotted results. The error bars have been obtained with the full width half maxima method. Due to the length of the Gaussian shape, this method leads to large error bars. Despite this, we can observe a slow linear growth of field voltage with transit time, with a gradient of $2.07 \cdot 10^{-5} \pm 9.12 \cdot^{-7}$ and an intercept of -8.03 ± 0.52. -MAKE IT MORE READABLE + CHANGE FORMAT + ERROR BARS & THEIR COMMENT NEED CORRECTION

lectors at various distances from the probe, as seen in Figure 3. We observe an unexpected skew in the Gaussian shape as the distance from the probe to the capacitor grows. Figure 10 illustrates this effect. In this figure, the previously discussed carrier properties remain true across all collectors, and therefore are not affected or related to this particular effect.

WHAT OTHER RESULTS AM I MISSING HERE? –TEMPERATURE!!!

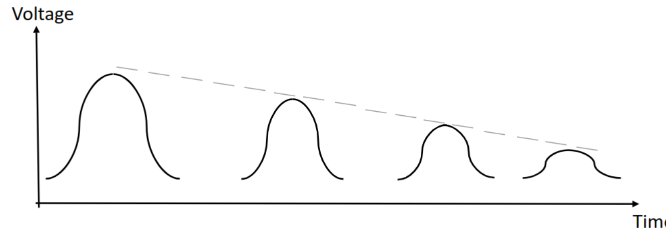

FIG. 8: Graph showcasing the observed evolution of the carrier distribution and decay following the carrier injection across time. As time passes, the Gaussian distribution slowly decreases and loses its shape. -ADD C1,C2,C3,C4 POSITIONS IN THE TIME AXIS

V. GENERAL DISCUSSION

A. Mobility

As seen in the results section, through experimentation we have observed a correlation between carrier injection input voltage and time duration with carrier mobility. This relation is supported by theory through the following equation:

$$V = \frac{d_3 L}{\mu} \times \frac{1}{t} \tag{7}$$

The relationship allows us to relate our existing data with a linear plot of our systems' received voltage against the inverse of the time measured time, which results in a gradient of $\frac{d_3 L}{\mu}$ that allows us to infer the observed mobility. Using distance $d_3 = 225\mu$m and L $= 950\mu$m, as per Figure 3, we obtain a gradient of linear fit of $2.07 \times 10^{-5} \pm 9.12 \times 10^{-7}$. This gives us a mobility of $\mu = 103.31$ cm^2/Vs. The uncertainty of this mobility is evaluated by:

$$\Delta\mu \approx \left.\frac{d\mu}{d\text{gradient}}\right|_{\langle\text{gradient}\rangle} \times \Delta\text{gradient} \tag{8}$$

and is equal to 4.57 cm^2/Vs. Thus giving us a final mobility of 103.31 ± 4.57 cm^2/Vs. Our expected mobility should be in the range of 300 to 500 cm^2/Vs [5]. These results lead us to suspect the presence of dopants in the probe. Doping refers to the introduction of impurities in a material. Dopants are often defined as intentionally introduced impurities into a material. Given laboratory constraints, we were unable to obtain documentation on our tested probes and therefore cannot confirm on the original purity of these. Nonetheless, regardless of the initial purity of the probes, it is important to know that silicon probes may become less pure over time due to environmental factors such as exposure to moisture, heat, chemical and physical stress, or student misuse of lab equipment. The presence of impurities will have an effect on the predicted mobility ranges.

B. Diffusion

The consistent presence of a data "skew" across results obtained in all collectors across multiple voltage ranges lead us to believe that the observed skew effect across collectors, discussed in our result section, is caused by the time evolution of the diffusion effects as they occur across the probe. Figure 8 showcases how the diffusion losses of the carrier injection evolve through time and thus become smaller and smaller in the voltage range, which causes a seemed skew of the data across collectors. This effect gives us an insight on the evolution of diffusion across the material. In addition to this observation, we further study the diffusion of carriers through the evaluation of the diffusion coefficient, given by the equation:

$$t_p^2 = t^3 \cdot \frac{16 \ln(2) D_h}{d_3^2} \tag{9}$$

Equation 9 gives us a diffusion coefficient $D_h = 13.27 \pm 1.28\ \mathrm{cm}^2/\mathrm{s}$. The expected diffusion coefficient of pure silicon is approximately 12 cm^2/s [5]. In the previous subsection, we observed that the expected mobility of our probe was not consistent with the expected values for pure silicon. As mentioned in the subsection, a natural cause of this could be the use of a doped material. Doped semiconductor diffusion coefficients can decrease up to 2 cm^2/s. Using data from collector 2 we obtained a diffusion coefficient $D_h = 2.89 \pm 0.85\ \mathrm{cm}^2/\mathrm{s}$. This result seems more consistent with previous evidence, and therefore is the one we utilized for further analysis.

It is important to note that these considerable differences between data across collectors should not be present, regardless of wherever the probe is doped or not. There are many possible causes for these discrepancies, ranging from experimental error to issues with sample preparation or measurement techniques. Therefore, it is important to carefully analyse and control for these factors in future experiments. Further investigation may be necessary to understand the underlying causes of the observed differences in diffusion coefficients and mobility values. This could include more detailed analysis of the material properties and composition, as well as more rigorous testing and calibration of the experimental setup.

Using our diffusion coefficient $D_h = 2.89 \pm 0.85\ \mathrm{cm}^2/\mathrm{s}$, and Einstein's relationship for a semiconductor (Equation 6), we obtain a semiconductor temperature of $T = 324 \pm 95\mathrm{K}$, which corresponds to $51.85 \pm 0.95°\mathrm{C}$. Experimentally the expected temperature value would have been of $20 \pm 1°\mathrm{C}$, therefore once again suggesting that the material is behaving differently than expected for undoped silicon. This discrepancy in temperature could be attributed to the heat generated by the dopant atoms, which can significantly alter the thermal behaviour of the material.

VI. CONCLUSION

In conclusion, the university may want to consider buying some new silicon probes. In this experiment, consistent and expected carrier behaviour was demonstrated across a silicon probe. However, the observed errors in the majority of results suggest the presence of impurities in the probes. Further investigations are required to confirm the presence of impurities and their effects on the experiment. These findings highlight the complex and multifaceted nature of semiconductor diffusion and mobility, and underscore the importance of careful measurement and analysis in this field.

VII. MY ROLE ON THE PROJECT

As one of my team's experimentalists, my work on the project focused on obtaining workable data from the experimental set-up and designing tests that were both relevant to our desired project extensions and yielded workable results. In addition to this, through my secondary role as a project manager, I managed the documentation for the team and fulfilled small administrative duties such as setting up and or moving meetings with our project supervisor. As a general team member, I also supported and worked in all other aspects of the project at a smaller scale.

VIII. REFERENCES

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CREATE REPO WITH DATA AND CODE!!!

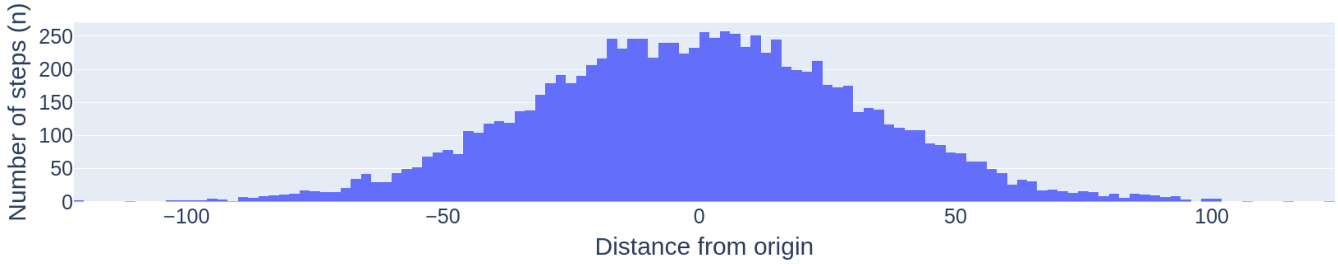

FIG. 9: Results of a simulated 1D quantum walk representing the diffusion of Drude like electrons through a conducting material. The obtained graph showcases a Gaussian distribution when plotting the number of steps taken by the walker (in this case, the electron moving through an arbitrary time unit). These results are consistent with theoretical predictions.

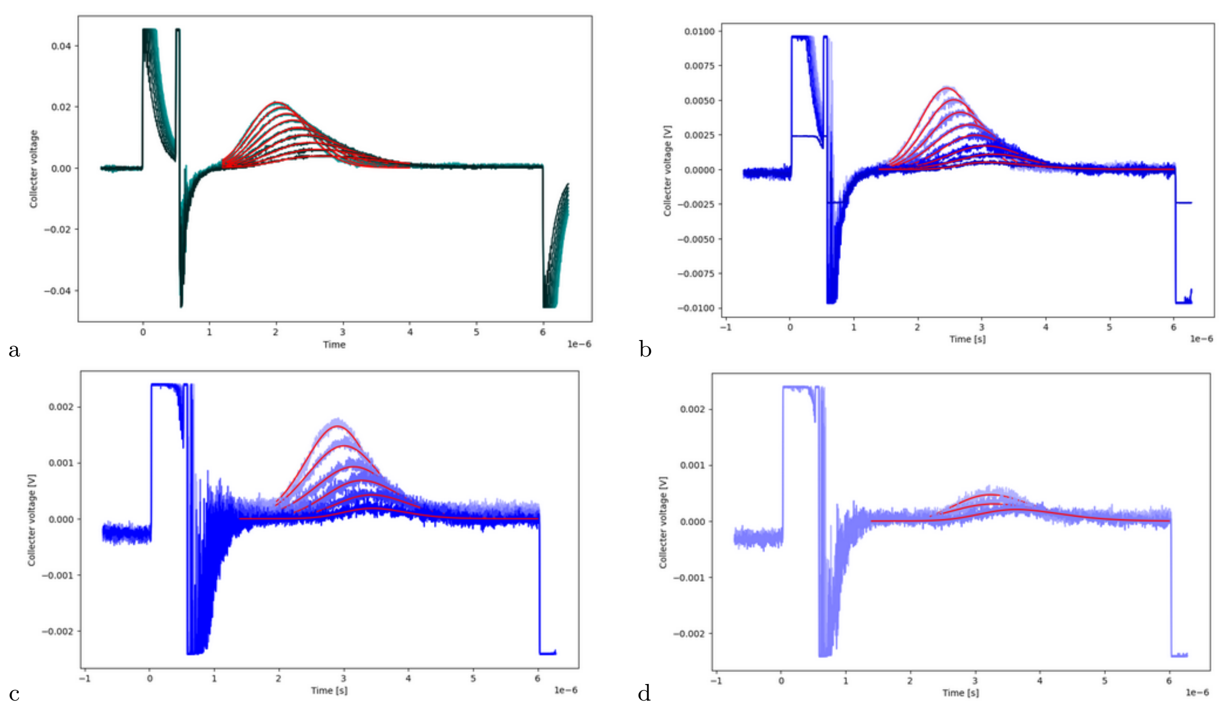

FIG. 10: From left to right, these graphics showcase the obtained collector voltage against time from the closes to the farthest collector from the tested probe. The axis in each of these graphs have been designed to better showcase each individual graph, but are not consistent against each other. One should consider this when comparing the obtained results. As one can observe, the farthest from the probe the capacitor is, the smaller and less Gaussian like the carrier distribution becomes. (a) Collector 1, (b) Collector 2, (c) Collector 3, and (d) Collector 4 - MAKE THE AXIS MORE READABLE AND THE COLOURS MORE CONSISTENT