Semiconductors lab EEE262

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Abstract

This lab report is based around the semiconductor creation of a generic Schottky diode named after Walter H. Schottky

1 Introduction

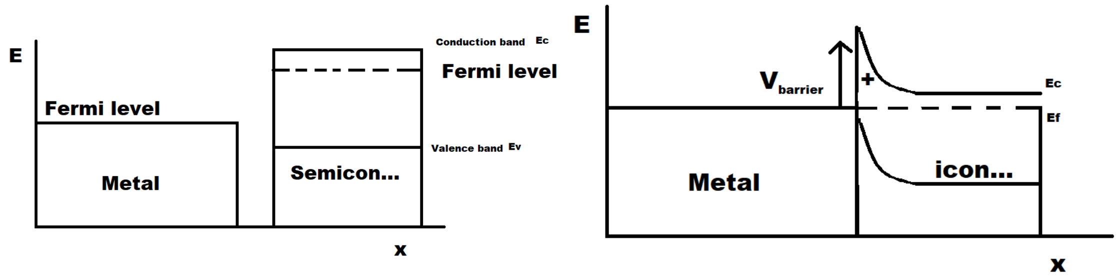
A Schottky diode, in comparison to a generic diode such as the venerable 1n4001, has a much lower voltage drop being closer to 0.2 volts compared to the usual 0.7 volts in turn lowering the power dissipation. On top of this the Schottky has a much faster recovery time meaning it can be used in higher frequency applications(hundreds of hertz) without letting current flow backwards. You may wonder why we ever wouldn't use a Schottky diode, unfortunately the negative half of our familiar V-I diode graph isn't as ideal as the breakdown voltage of a Schottky diode is considerably lower with common values being around 30 volts. Not only this but a Schottky diode usually has a reverse leakage current around 200 times higher and in certain situations can reach milliamps, certainly not good if you're making sensitive equipment. Due to these qualities though Schottky diodes are very useful in high frequency applications such as radio systems (RF systems) or switch mode power supplies.[1]

2 Theory overview

2.1 Metal-semiconductor contacts

A metal and semiconductor will always have different fermi levels(average electron energy), upon contact of the two materials these fermi levels will cause a electric field over the device due to the difference in charge density, as of this the electrons will defuse until the fermi levels are equal, shown in Figure:1a and Figure: 1b.[2] As of this electrons enter the metal and diffuse away from the semiconductor leaving the area close to the contact positively charged creating a barrier electrons struggle to overcome (due to the charge ramp) as shown in Figure:1b. There will always be this voltage barrier for a metal-semiconductor join given by

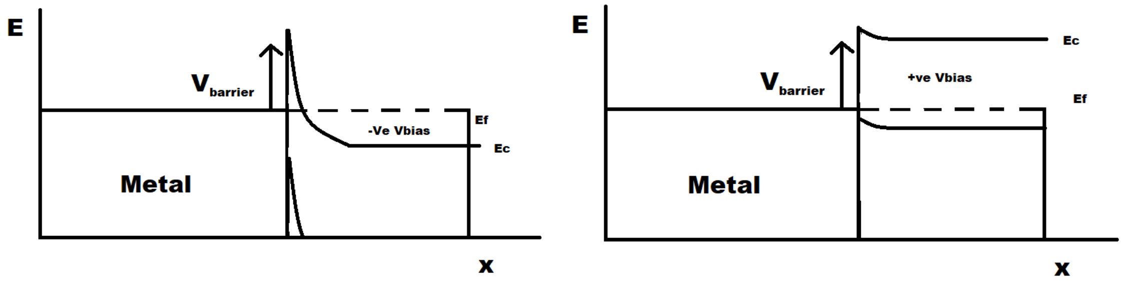
$$V_{Barrier} = \phi_M - \chi_s \tag{1}$$



(a) Metal and semiconductor before touching

(b) Junction after charge diffusion

Figure 1: Before and after contact



(a) Schottky junction with a negative voltage applied (b) Schottky junction with a positive voltage applied

Figure 2: Voltage bias applied

($V_{Barrier}$=Voltage barrier; ϕ_M=Work function of the metal; χ_s=Semiconductor electron affinity)
Electrons must either jump over this ramp or quantum tunnel through in both cases the lower the ramp height the easier (more probable).

2.1.1 Rectifying(Schottky)

A Schottky contact is made naturally by bringing the two materials together creating a barrier as previously explained, after the electrons have moved to create the voltage barrier there is now no difference in voltage and therefore no current flowing either way. As of the constant voltage barrier, flow of current (metal to semiconductor) is constant, just when no field is applied the flow of current semiconductor to metal is equal, when a reverse voltage is applied the semiconductor conduction band is shifted down creating a steeper hill for the electrons to jump when traveling semiconductor to metal as of this there is the constant flow of current, metal to semiconductor which is our diodes reverse leakage. When the voltage is applied forwards though our semiconductor band increases in energy flattening the hill increasing the probability of jumping the barrier (while the barrier for metal to semiconductor is still constant) and allowing free flow of electrons as soon as the voltage applied cancels the semiconductor charge hill.[3]

2.1.2 Ohmic

If this barrier is always there then we cannot minimize the likelihood for the electron to jump as it is based majority off this barrier height so instead we must focus on increasing the probability for the electron to tunnel through (which intuitively is more probable the thinner the ramp) to change the width we must look at the equation

$$W = \sqrt{\frac{2\varepsilon_0\varepsilon_r(V_{Barrier} + V_{Bias})}{qN_d}} \tag{2}$$

(ε_0 = permittivity of free space; ε_r=relative permittivity of semiconductor; $V_{Barrier}$=Voltage barrier; V_{Bias}=the voltage applied across the device; q=electron charge; N_d=Semiconductor doping density)
So to decrease the width we must increase the doping density of the semiconductor. Therefore to create a ohmic contact we must dope the semiconductor heavily at where the join is made so that the probability to tunnel is nearly equal to 1 (the closer the better) at this point the probability to tunnel is far greater than that of the electron to jump.

2.2 Schottky Characteristics

A Schottky diode follows almost exactly the same graph as a basic diode where after a forward voltage (around 0.2V) the current exponentially increases and in the negative region a small amount (considerably larger than normal) of reverse leakage current and then a breakdown voltage (Considerably smaller than normal) where the current once again increases, in the opposite direction, exponentially.

3 Device fabrication

3.1 Safety

For every type of hazard, as separately described below, there are risk assessments available to all students. The majority of safety in this lab is completed by simply being competent about the surroundings and handling of equipment.

3.1.1 Chemicals

As one may expect for a university clean lab, there are many chemicals in the room, some of which used for this practical and others not used currently. It is important to treat every unknown substance as a threat and identify the best method to minimize risk whether that be wearing gloves while handling these substances or simply staying away from them. The two chemicals used in this lab are class C and D (C- Corrosive and Irritating; D-very toxic from single exposure) and so safety gloves are a must while handling these.

3.1.2 Hot surfaces

In this lab a hotplate will be used and so follow basic competency and treat it as you would hob-like equipment at home.

3.1.3 Electricity

As with most Electronic and Electrical Engineering labs there will be access to live conductors and therefore a chance of electrocution. Hopefully by being a EEE student electrical competency should be already logical but a helpful reminder to never put out electrical fires with water can't go amiss.

3.1.4 Liquid nitrogen

A thermal evaporator uses liquid nitrogen to produce the operating conditions, after the main point of be weary when in close proximity due to the temperature it is also advised to understand that this nitrogen as it boils displaces your average air and so breathing for a long time nearby is also ill advised.

3.1.5 Sharps

As we are dealing with semiconductors these devices use very small contacts and so must be probed delicately and so these probes are needle like and is a good idea to keep fingers away from the probing area if possible. This lab also has scalpels and glass in and therefore is a good idea to handle these with care and competency.

3.1.6 UV light

The mask aligner in the lab uses a UV lamp which if directly exposed into the eyes for long periods of time may cause permanent damage, so avoid eye contact if possible.

3.2 Clean-room Specs

To maintain a class 7 (ISO) standard the levels of dust must be kept to a minimum by restricting contaminants (which are usually human caused) by covering skin and having clothes covered, keeping the quantities of dust below that shown in Table 1:

Particle size(μm)	0.1	0.2	0.3	0.5	1	5
Maximum particle density(m^{-3})	1.0×10^7	2.37×10^6	1.02×10^5	3.52×10^4	8.32×10^3	2.93×10^2

Table 1: Clean-room data for ISO 7

3.3 Cleaning

Semiconductors are usually based around materials on the micro scale and so tiny amounts of dust or contaminants can drastically effect the performance and characteristics of the device. Due to this cleaning is an important step before device creation. To do this the semiconductor is placed in heated butyl ethanoate(NBA) and rubbed using a soaked cotton bud to remove organics from the sample.The NBA must now be removed this is done using acetone to displace off the NBA. Finally the sample is quickly placed into isopropyl alcohol as when acetone dries, Which it does quickly, it leaves stains on the surface which are removed by the alcohol.The alcohol drops are then removed using a blast of pressurized filtered nitrogen.

3.4 Mounting process

The small sample is then mounted on a glass slide to make the photolithograpy easier. This is done by using wax, Dental wax!

3.5 Photolithography process

Now the fun bit! This starts with a couple more cleaning steps to make sure the sample is as clean as possible. To begin the sample is heated for around a minute to evaporate off any moisture, the sample is then placed into a spinner and spun at 4000 RPM which should create a high enough force to make contaminants shoot off(filtered nitrogen helps this happen). Now the actual photoresist chemical is dropped onto the GaAs, and placed into the spinner again and spun, as it spins the photoresist will spread out and leave a thin coating (around 1 micron thick) of the photoresist on the device. The sample is then placed under a mask aligner with a mask(like a stencil made of chromeium) where you slightly alter the position of the semiconductor in relation to the mask to align the two. When the semiconductor is aligned with the mask a UV light is used to selectively expose the photoresist. The exposed photoresist turns to a polymer and is removed when in contact with developer (AZ) leaving the pattern in the device, the developer is removed by cleaning with de-ionized water which is in turn removed by a filtered nitrogen blast.

3.6 Metallisation process

The sample is then placed in a vacuum chamber at 1 nano bar (thermal evaporator) where a tungsten coil is placed above the sample (the further the tungsten coil the more consistent the layer but also the more metal needed) the coil is filled with aluminium and when the coil passes current it heats up and boils the aluminium and as it's in a vaccum it gassifies and almost liniarly covers the surface with the metal, including the chamber walls! This layer of aluminium is around 0.2 microns thick! Tungsten is used for the coil as of its property to not react with substances and as it has the highest melting point of any element.

3.7 Lift-Off

After this metal layer has been deposited we now want to remove it on certain sections which is done by removing the photoresist that was placed on the device, this is done by placing the sample into warm acetone which will remove the photoresist. The more accurate and in focus the mask was in the photo the better the edges of the photoresist are and should react easier. Adding flow to the acetone should increase the chances as well.

4 Ohmic contact

As discussed in section 2.1.2 an Ohmic contact is made by heavily doping the semiconductor in this case we used indium-germanium to heavily dope the connection. This is only doped on the surface at 20 nano meters thick with a 100 nano meter gold layer on top which keeps the indium-germanium in and to be useful to create an easy contact. This is then heated in a furnace to join the semiconductors and diffuse them into each-others surfaces.

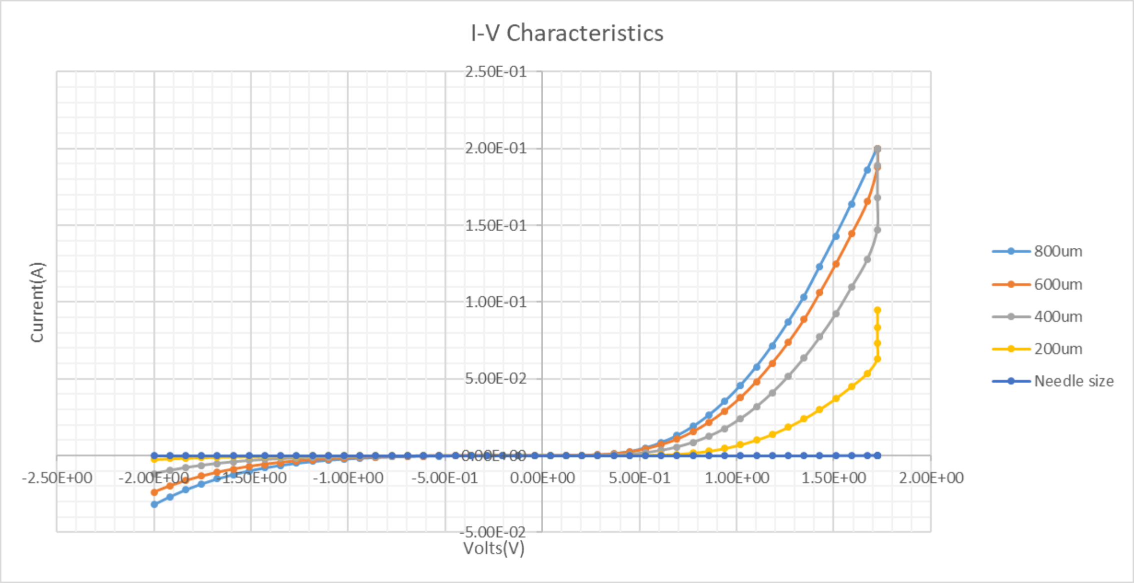


Figure 3: V-I characteristics graph for all values

5 Device characterization

Once the device has been manufactured with a schottky contact on one side and ohmic on the other(otherwise it's a double ended diode and won't conduct). The well ingrained diode formula as shown:

$$j = j_o(e^{\frac{qv}{nk_bT}} - 1) \tag{3}$$

can be used in our results case by graphing the log of our J values and where the extrapolation of our linear section of the graph intercepts the axis is our log of j_o value and then we can find the value of n assuming that the -1 is negligible in comparison to the exponential term , which is valid when or exponential is large so we must take the gradient at the furthest point possible which should appear linear when our J is on a log scale if the 1 is ignored.

5.1 I-V characteristics

5.1.1 Method

For the I-V results the specimen was placed under a microscope and connections made using needle connections onto the aluminum contacts where a step function was applied from -2 to 2 volts with the pure results put into Table: 6/7 for each size. Unfortunately the software/hardware must use floating point integers which when written decimally can give minuscule errors at the least significant bit making the tables messy and filled with zeroes and nines.

5.1.2 Results

The results tables can be seen in Table:6/7 and the graphs are shown in Figure: 3. From the graph we can see the normal diode VI characteristics are followed with our steep exponential gain after a certain turn on voltage.These curves will not continue on forever as when the current increases the semiconductor starts changing temperature which we can see in equation 3 can drastically change the output. When we work out our terms we assume that the current in the device is constant throughout the area contacted with aluminium therefore the current density is given by $\frac{I}{\pi*(\frac{d}{2})^2}$. As explained in section 5 we can extrapolate the linear section of the graph in Figure: 4 and get our j_o value at the Y intercept. By using excel to extrapolate the linear section we get a value of between $23,765m^{-2}$ and $29,525m^{-2}$ as we take the log of the intercept and then using this value to work out our n value using Equation (3) giving us between 17.5 and 12.8 as shown in Table :2. From the non-ideality factor (n) we can tell the diodes we made weren't very good but also the smaller the device the better our value(Good news for making them!).

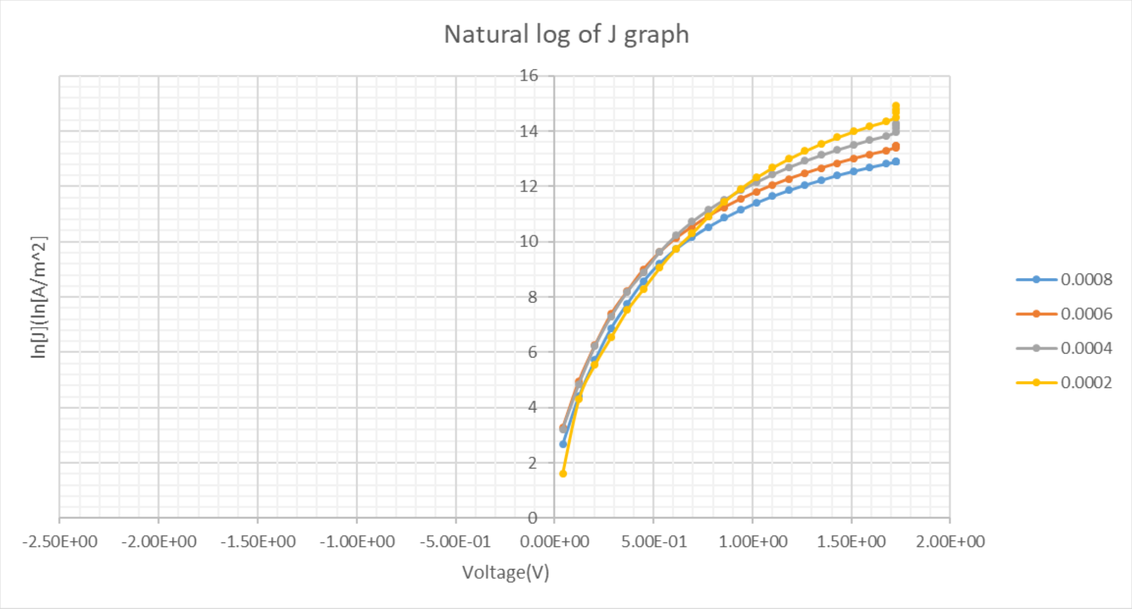


Figure 4: Ln of current densisty graph

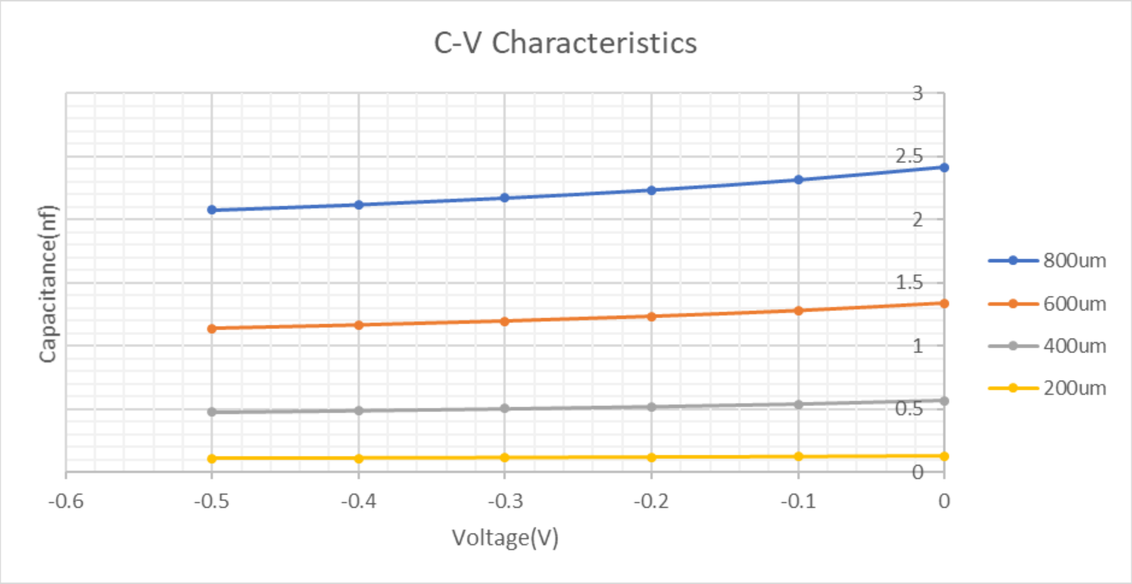


Figure 5: C-V characteristics graph for all values

Diameter(um)	800	600	400	200
Y intercept(I/m^2)	10.076	10.151	10.274	10.293
J0(I/m^2)	23765	25616	28969	29525
n	17.5	15.7	14.2	12.8

Table 2: Table of calculated saturation current and non-ideality factor

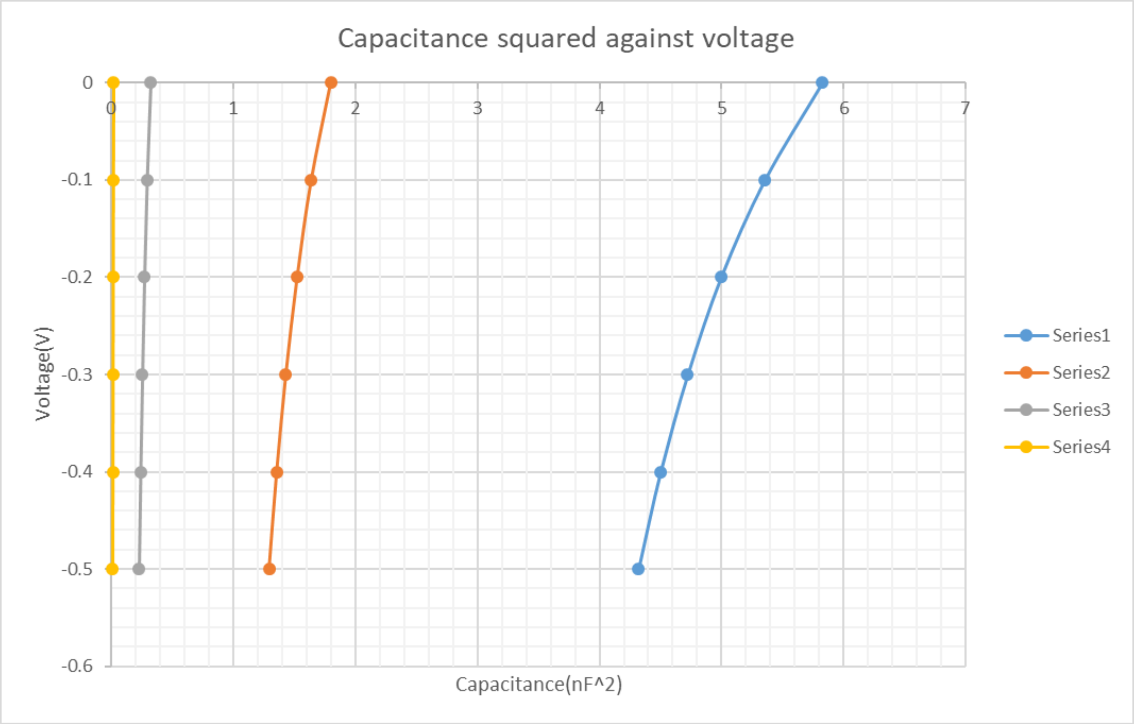


Figure 6: C^2-V characteristics graph for all values

5.2 C-V characteristics

5.2.1 Method

The C-V characteristics are measured using the same setup except using a LCR meter to get the value of capacitance in the system and the phase angle. As we are measuring capacitance on the nano scale any change in wire separation could drastically change the measured capacitance meaning when taking these results any attempt at changing the system isn't advised. after taking these results we can graph the value of v against c^2 and the gradient $(\frac{dv}{dc^2})$ times by a device constant as shown below in equation 4:

$$N_d = \frac{2}{A^2 q \varepsilon_o \varepsilon_r} \cdot \frac{dv}{dc^2} \tag{4}$$

5.2.2 Results

As we can see from Figure 5: the larger the plate size the larger the capacitance which makes sense given the capacitor equation where the capacitance is directly proportional to area over separation so our larger diode has larger area like a capacitor plate. We also see that over time the larger the reverse voltage (more -ve being larger) the capacitance goes down meaning our voltage barrier is getting skinnier and skinnier just like we see in our theoretical section Figure 2a. Using graph Figure 6: we can actually work out our doping density as described in 5.2.1. i used the value for the widest diode where the graph seemed linear ($600\mu m$) as i thought this would have the least unaccounted losses and i got a value of $1.321 \cdot 10^{24}$ which seems reasonable for a doping density.

Using this value as our doping density we can use the equation:

$$C = A\sqrt{\frac{q\varepsilon_0\varepsilon_r N_d}{2 \cdot (V_{Barrier} + V_{Bias})}} \tag{5}$$

to calculate the value of our voltage barrier when we re-arrange for $V_{Barrier}$ giving us a value of 0.54V as our voltage barrier which seems about right given that most contacts to GaAs have a voltage barrier of around 0.8 volts but we evidently have a fair bit of error in our calculations.

6 Discussion/Conclusion

Overall the values calculated and those of theoretical do vary due to impurities, ineficiencies and non constant materials but many different sized diodes have been made each with pros and cons to each size but overall each fabrication step worked and made a functioning diode seen by the I-V graph and C-V characteristics gathered from the sample and with a report written thats all of our lab aims met.

7 Appendix

7.1 Raw Data

Volts(V)	Capacitance(nF)	Phase angle(°)
0	2.414	-84.94
-0.1	2.314	-86.24
-0.2	2.235	-84.4
-0.3	2.173	-81.2
-0.4	2.121	-77.1
-0.5	2.078	-72.4

Table 3: 800 μm voltage-capacitance

Volts(V)	Capacitance(nF)	Phase angle(°)
0	1.341	-85.3
-0.1	1.280	-86.5
-0.2	1.234	-84.5
-0.3	1.196	-81.0
-0.4	1.164	-76.2
-0.5	1.137	-70.3

Table 4: 600 μm voltage-capacitance

Volts(V)	Capacitance(nF)	Phase angle(°)
0	0.5684	-86.1
-0.1	0.5413	-87.2
-0.2	0.5213	-85.3
-0.3	0.5053	-81.8
-0.4	0.4907	-76.4
-0.5	0.4783	-69.4

Table 5: 400 μm voltage-capacitance

Volts(V)	Capacitance(nF)	Phase angle(°)
0	0.129	-87.9
-0.1	0.123	-87.8
-0.2	0.119	-86.1
-0.3	0.115	-82.8
-0.4	0.112	-77.4
-0.5	0.109	-69.7

Table 6: 200 μm voltage-capacitance

References

[1] G. Williams, "Semiconductor laboratory: Fabrication and assessment of a schottky diode." Online, Oct. 2017.

[2] S. Montanari, "Device physics, theoretical basis." Web Article, Aug. 2005.

[3] A. Zukauskas, "Schottky diode." Web Article, 2002.

Voltage(V) 800um	Current(A) 800um	Voltage2(V)600um	Current2(A)600um
-2	-3.1990499999999998E-2	-2	-2.3847299999999998E-2
-1.9183699999999999	-2.68183E-2	-1.9183699999999999	-1.9823299999999999E-2
-1.83673	-2.2321799999999999E-2	-1.83673	-1.63616E-2
-1.7551000000000001	-1.84443E-2	-1.7551000000000001	-1.34243E-2
-1.67347	-1.5140499999999999E-2	-1.67347	-1.0942800000000001E-2
-1.5918399999999999	-1.2337300000000001E-2	-1.5918399999999999	-8.8599999999999998E-3
-1.5102	-9.9483000000000002E-3	-1.5102100000000001	-7.0897399999999998E-3
-1.42858	-7.9571799999999995E-3	-1.42859	-5.6642899999999998E-3
-1.3469500000000001	-6.3235799999999997E-3	-1.3469500000000001	-4.4829700000000002E-3
-1.2653300000000001	-4.9681500000000002E-3	-1.26532	-3.5148200000000001E-3
-1.1836800000000001	-3.8556799999999998E-3	-1.1836800000000001	-2.7272400000000001E-3
-1.10205	-2.9513600000000001E-3	-1.10205	-2.09194E-3
-1.0204200000000001	-2.2253300000000002E-3	-1.0204200000000001	-1.5839999999999999E-3
-0.93878600000000001	-1.6496200000000001E-3	-0.93878600000000001	-1.18227E-3
-0.85714500000000005	-1.19972E-3	-0.85714299999999999	-8.6644100000000002E-4
-0.77551300000000001	-8.5091799999999999E-4	-0.77551199999999998	-6.2611999999999998E-4
-0.69388300000000003	-5.9137800000000004E-4	-0.69388300000000003	-4.4251000000000002E-4
-0.61224199999999995	-3.9947799999999999E-4	-0.61224199999999995	-3.0530599999999998E-4
-0.53061100000000005	-2.6151000000000001E-4	-0.53061100000000005	-2.0552499999999999E-4
-0.44898199999999999	-1.64933E-4	-0.44898199999999999	-1.3397800000000001E-4
-0.36735099999999998	-9.9018999999999995E-5	-0.36737500000000001	-8.2992700000000002E-5
-0.28570800000000002	-5.6367199999999998E-5	-0.28569699999999998	-4.9387600000000001E-5
-0.2040913	-3.05097E-5	-0.20408370000000001	-2.8117099999999999E-5
-0.1224871	-1.48245E-5	-0.12245490000000001	-1.4561399999999999E-5
-4.0834599999999999E-2	-4.4785499999999997E-6	-4.0823499999999999E-2	-4.4861600000000001E-6
4.0842200000000002E-2	7.1982199999999997E-6	4.08566E-2	7.4529100000000001E-6
0.1224769	4.1217999999999997E-5	0.1224769	4.0280000000000001E-5
0.20408419999999999	1.53955E-4	0.20408499999999999	1.48028E-4
0.28572900000000001	4.8753000000000002E-4	0.28573399999999999	4.5600399999999998E-4
0.367365	1.18972E-3	0.36736600000000003	1.04356E-3
0.44903900000000002	2.6871099999999999E-3	0.44905	2.2891500000000002E-3
0.53070899999999999	5.1029600000000001E-3	0.53073099999999995	4.2476199999999997E-3
0.61234500000000003	8.5213100000000007E-3	0.61239699999999997	7.0546799999999998E-3
0.69388099999999997	1.30592E-2	0.69388300000000003	1.06202E-2
0.77551000000000003	1.89573E-2	0.77551300000000001	1.55105E-2
0.85714199999999996	2.6339899999999999E-2	0.85714100000000004	2.1585900000000002E-2
0.93878200000000001	3.5233399999999998E-2	0.93878399999999995	2.9022599999999999E-2
1.02041	4.57317E-2	1.02041	3.7779899999999998E-2
1.1020399999999999	5.79222E-2	1.1020399999999999	4.8241399999999997E-2
1.18367	7.1623999999999993E-2	1.18367	6.0330000000000002E-2
1.2653099999999999	8.6845599999999995E-2	1.2653099999999999	7.3618699999999995E-2
1.34694	0.10344390000000001	1.34694	8.8572999999999999E-2
1.4285699999999999	0.123214	1.4285699999999999	0.106184
1.5102	0.143041	1.5102	0.12472800000000001
1.5918399999999999	0.16402	1.5918399999999999	0.144512
1.6734500000000001	0.18606500000000001	1.67347	0.165524
1.7234	0.19999500000000001	1.7550600000000001	0.18758
1.72401	0.19999600000000001	1.79992	0.199993
1.7245999999999999	0.19999500000000001	1.80105	0.19999500000000001
1.7250399999999999	0.19999700000000001	1.80196	0.19999600000000001

Table 7: 800/600 μm voltage-current pure data

Voltage3(V)400um	Current3(A)400um	Voltage4(V)200um	Current4(A)200um
-2	-1.17121E-2	-2	-2.4874300000000001E-3
-1.9183699999999999	-9.5857000000000008E-3	-1.9183699999999999	-1.9849400000000001E-3
-1.83674	-7.7868900000000003E-3	-1.83673	-1.5754199999999999E-3
-1.75512	-6.2979799999999999E-3	-1.7551000000000001	-1.2454300000000001E-3
-1.6734800000000001	-5.05887E-3	-1.67347	-9.8112000000000004E-4
-1.59185	-4.0292100000000001E-3	-1.5918399999999999	-7.6768400000000003E-4
-1.5102100000000001	-3.1928400000000002E-3	-1.5102	-6.0005699999999998E-4
-1.42858	-2.5148100000000001E-3	-1.4285699999999999	-4.6689799999999999E-4
-1.3469500000000001	-1.96561E-3	-1.34694	-3.6154299999999998E-4
-1.26532	-1.5234700000000001E-3	-1.2653099999999999	-2.7817E-4
-1.1836800000000001	-1.17041E-3	-1.18367	-2.1193000000000001E-4
-1.1020399999999999	-8.9075000000000005E-4	-1.1020399999999999	-1.60073E-4
-1.02041	-6.68167E-4	-1.02041	-1.20332E-4
-0.93878399999999995	-4.9645400000000001E-4	-0.93877999999999995	-8.9315999999999997E-5
-0.85714299999999999	-3.6319599999999998E-4	-0.85715600000000003	-6.4449999999999994E-5
-0.77551199999999998	-2.6186599999999998E-4	-0.77549699999999999	-4.6165599999999997E-5
-0.69388000000000005	-1.8521999999999999E-4	-0.69388799999999995	-3.29526E-5
-0.61224199999999995	-1.27515E-4	-0.61223899999999998	-2.3065400000000001E-5
-0.53061199999999997	-8.5060299999999996E-5	-0.53063700000000003	-1.51266E-5
-0.44899299999999998	-5.59109E-5	-0.44899099999999997	-9.4671999999999998E-6
-0.36737900000000001	-3.54713E-5	-0.36734	-6.3667499999999996E-6
-0.28572199999999998	-2.09309E-5	-0.28573900000000002	-4.0446799999999999E-6
-0.20411679999999999	-1.1511999999999999E-5	-0.20409389999999999	-1.91137E-6
-0.1224459	-6.1700999999999996E-6	-0.1224565	-5.8779000000000005E-7
-4.0830199999999997E-2	-2.4000700000000001E-6	-4.07321E-2	-4.7533099999999998E-7
4.0816400000000003E-2	3.1319099999999999E-6	4.10593E-2	1.5692700000000001E-7
0.1224759	1.58521E-5	0.12247039999999999	2.3023599999999999E-6
0.2042976	6.3336400000000006E-5	0.20410780000000001	8.1710300000000006E-6
0.28572399999999998	1.8588599999999999E-4	0.28573500000000002	2.2021399999999999E-5
0.36737399999999998	4.5422099999999999E-4	0.36751899999999998	5.8334500000000002E-5
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0.77562299999999995	8.7059000000000008E-3	0.77554000000000001	1.7172299999999999E-3
0.85714299999999999	1.2621500000000001E-2	0.85719400000000001	2.9406900000000001E-3
0.93878099999999998	1.7710400000000001E-2	0.93885300000000005	4.6990799999999996E-3
1.02041	2.4133700000000001E-2	1.0204899999999999	7.0820800000000001E-3
1.1020399999999999	3.1846800000000001E-2	1.1021300000000001	1.0151719999999999E-2
1.18367	4.1047800000000002E-2	1.18367	1.3876899999999999E-2
1.2653099999999999	5.1666400000000001E-2	1.2653099999999999	1.8479599999999999E-2
1.34694	6.3731300000000005E-2	1.34694	2.3934299999999999E-2
1.4285699999999999	7.7303800000000006E-2	1.4285699999999999	3.01722E-2
1.5102	9.2350799999999997E-2	1.5102	3.7223199999999998E-2
1.5918399999999999	0.109824	1.5918399999999999	4.5101799999999997E-2
1.67347	0.127998	1.67347	5.3741400000000002E-2
1.7551000000000001	0.147337	1.7551000000000001	6.3103999999999993E-2
1.83673	0.16775899999999999	1.83673	7.3101299999999994E-2
1.91828	0.18917400000000001	1.9183699999999999	8.3640300000000001E-2
1.95865	0.19999400000000001	2	9.4593700000000003E-2

Table 8: 400/200 μm voltage-current pure data