Schottky Barrier Diode

A case study of semiconductor analysis

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***Abstract*—Considering a model circuit for a Schottky barrier diode, we perform a series of experiments to characterise the electrical properties from which we can examine the details of the component. In general we compare the behaviour of the Schottky barrier diode with that of a PN-junction diode to contrast the properties and characterise the performance. With further analysis, we can identify semiconductor properties relating to the proper function of a diode.**

I. INTRODUCTION

The Schottky barrier diode (SBD) is a two-terminal device made from a junction between a metal and a semiconductor. It is used for radio frequency and high power applications and for the characterisation of semiconducting materials. For an ideal interface, the contact behaviour is determined by the difference in work functions. Considering a metal and a N-type semiconductor interface for the SBD,electrons will flow towards the metal as its work function ϕ_m is greater than the work function of the semiconductor ϕ_{sc} hence causing a build-up of potential at the contact V_c that will oppose the flow. The contact potential V_c can be calculated as $V_c = \dfrac{\phi_m - \phi_{sc}}{e}$. A depletion region is created in the semiconductor hence creating an associated capacitance that varies inversely with the width of the region. By applying voltage in reverse bias, we can increase this depletion region. For the purpose of these experiments, we consider $V_c = V_0 \approx 0.5V$ and we assume the model shown in Fig. 1 for the SBD where R_{leak} is the leakage resistance, C_{diode} is the diode capacitance, r_c is the resistance of the contacts and C_s is the stray capacitance of the SBD packaging.

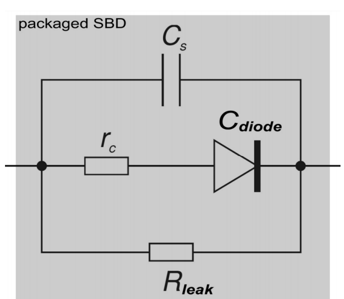

Fig. 1. SBD Model

In this investigation, we performed a series of experiments to determine the behaviour of the SBD model. This consisted of firstly calculating the capacitance of the SBD in reverse bias by measuring the frequency change with voltage with the aim of calculating the stray capacitance c_s of the SBD as well as the donor density N_D of the semiconductor in turn to calculate the actual capacitance of the diode C_{diode}. Then secondly measuring the current and voltage in reverse bias we can determine the leakage resistance R_{Leak} of the SBD and the reverse saturation current I_s which can be compared to the PND. We can then test the SBD in forward bias to calculate the ideality factor η. In practice for the latter experiment, we have to consider both a weak forward bias and a strong forward bias to characterise the diode in detail as the resistance of the contacts r_c are not negligible in strong forward bias. Hence by considering strong forward bias separately, we are able to calculate the contacts resistance r_c. The overall aim of this investigation was to characterise the SBD in terms of its electrical as well as its semiconductor properties.

II. METHOD AND RESULTS

A. C-V Measurements

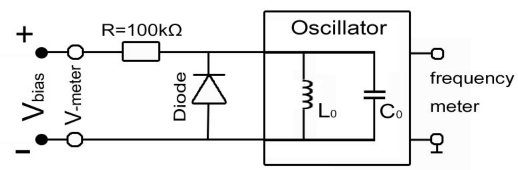

Fig. 2. Circuit diagram for CV measurements

For the circuit in Fig. 2, we vary the reverse bias voltage and measure the frequency, from which we can calculate the SBD capacitance C_{SBD}.

For stray capacitance C_0 and the added capacitance C_d, the frequency f_d (when C_d is present) and the frequency f_0 (when there is no added capacitance) can be calculated from the following constant of proportionality:

$$\frac{1}{4\pi^2 L} = C_0 f_0^2 = (C_0 + C_d) f_d^2$$

As C_0 and f_0 are known measured variables (given in Appendix 1), we can now calculate the capacitance C_d for any given frequency f_d.

The equation for the internal capacitance of the SBD depending on the reverse voltage bias V_{rev} is given by Eq. 1.

$$C_{\text{diode}} = A\Big(\frac{\epsilon_0 \epsilon_r q N_D}{2}\Big)^{\frac{1}{2}} (V_0 - V_{rev})^{-\frac{1}{2}} \tag{1}$$

For small currents, r_c has negligible effects so we can consider the total resistance of the SBD to be the following:

$$C_{\text{SBD}} = C_{\text{diode}} + C_s$$

Now if we write this function as $y = mx + c$ for plotting the graph, we get the following:

$$C_{\text{SBD}} = \frac{C_{\text{diode}}}{(V_0 - V_{rev})^{-\frac{1}{2}}} (V_0 - V_{rev})^{-\frac{1}{2}} + C_s$$

$$\frac{C_{\text{diode}}}{(V_0 - V_{rev})^{-\frac{1}{2}}} = m = A\Big(\frac{\epsilon_0 \epsilon_r q N_D}{2}\Big)^{\frac{1}{2}} \tag{2}$$

By substituting for $\frac{C_{\text{diode}}}{(V_0 - V_{rev})^{-\frac{1}{2}}}$ using Eq. 1 we get the following equation for the graph:

$$C_{\text{SBD}} = m(V_0 - V_{rev})^{-\frac{1}{2}} + C_s$$

where Eq. 2 is the equation for the gradient and $c = C_s$ is the y-intercept. Therefore we can plot C_{SBD} on the y-axis and $(V_0 - V_{rev})^{-\frac{1}{2}}$ on the x-axis to find N_D and C_s.

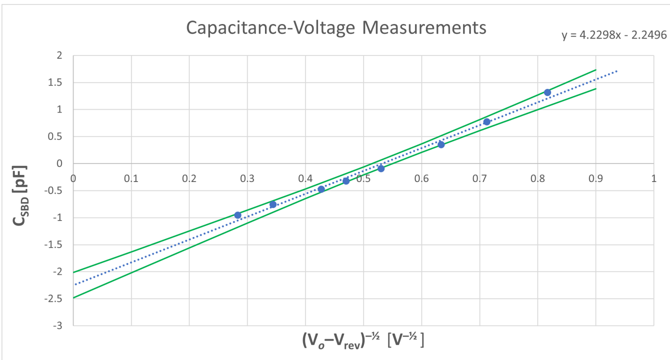

Fig. 3. SBD capacitance graph with 95% confidence intervals

From the y-intercepts of 3, we get $C_s = -2.25 \pm 0.23pF$ for the 95% confidence interval. From the gradient of the line of best fit, we can calculate N_D however to go a step further, we can use the 95% confidence intervals to calculate the minimum and the maximum allowed gradients. Then by substituting these gradients into Eq. 2 we can rearrange to get a lower bound and an upper bound for N_D.

$m = 4.2298 \pm 0.4526$ to 4dp
$N_D = 2.34_{10^{21}} m^{-3}$ in the 95 % confidence interval of $[1.87, 2.87]$. Note that the non-linear difference in bounds arises from the square root in Eq. 2.

B. I-V Measurements

Reverse Bias

The aim of this stage was to plot a I-V graph to determine the reverse bias saturation current I_s at the point of non-linearity.
In this circuit shown in Fig. 4, we measure the voltage across $100k\Omega$ resistor and hence we can calculate the voltage using $I = V/R$. So here we simply vary the reverse bias voltage and measure the voltage across the resistor. We can then work out the current for each corresponding voltage and plot an I-V graph to find the point of current saturation.

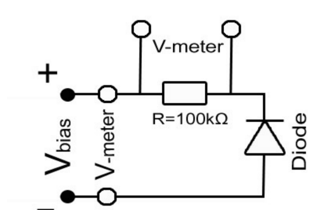

Fig. 4. Circuit diagram for IV measurements in reverse bias

From the equation below, we can determine the properties of the graph:

$$I_{rev} = \frac{1}{R_{\text{Leak}}} V_{rev} + I_s\left(\frac{qV_{rev}}{\eta kT} - 1\right)$$

Although V_{rev} is present in the y-intercept (meaning that this is not actually a linear relationship), by plotting the graph we can see that linearity is obeyed up to the point of saturation. Therefore we can estimate I_s and calculate $R_{\text{Leak}} = 1/m$ where m is the gradient of the line of best fit.

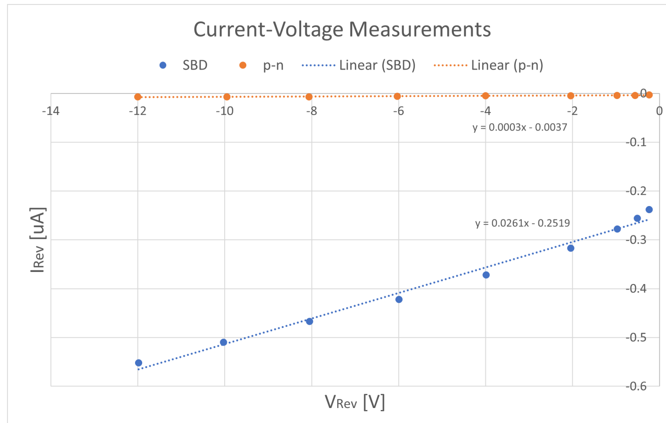

Fig. 5. I-V reverse bias graph for SBD and PND

Considering three different gradients to give three different R_{Leak}, one for all points (minimum estimate of R_{Leak}), one that excludes points past saturation (medium estimate of R_{Leak}) and one that only consider the first five linear points (maximum estimate of R_{Leak}):
Min $R_{Leak} = 38.3M\Omega$
Med $R_{Leak} = 40.9M\Omega$
Max $R_{Leak} = 44.7M\Omega$

Weak Forward Bias

With the circuit setup shown in Fig. 6, we try to obtain specific values of current by changing the reverse bias voltage and then we measure the voltage across the diode.

By rearranging the equation $I_f = I_s\left(e^{\frac{q}{kT}\cdot\frac{V}{\eta}}\right)$ into the following form:
$\ln(\frac{I_f}{I_s} + 1) = \frac{\left(\frac{q}{kT}\right)}{\eta}V$
where η is the ideality factor of the SBD.

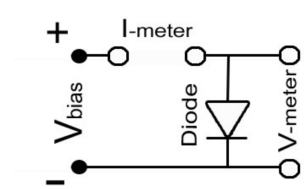

Fig. 6. Circuit diagram for IV measurements in forward bias

We can plot the graph with $\ln(\frac{I_f}{I_s} + 1)$ on the y-axis and V on the x-axis. We can then use the gradient m of the line of best fit to determine η.
$\eta = \frac{q}{mkT}$

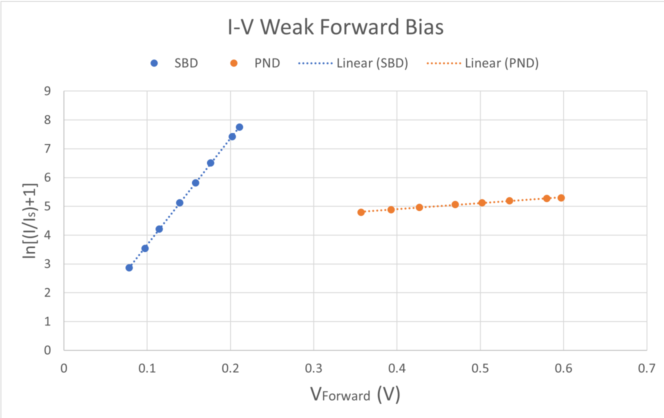

Fig. 7. I-V weak forward bias graph for SBD and PND

By measuring the temperature of the SBD with a thermometer, we find the temperature to be $T = 298K$ and therefore using the gradient of the line of best fit from the graph, we find the ideality factor of the SBD to be $\eta = 1.054$ to 3dp.

Strong Forward Bias

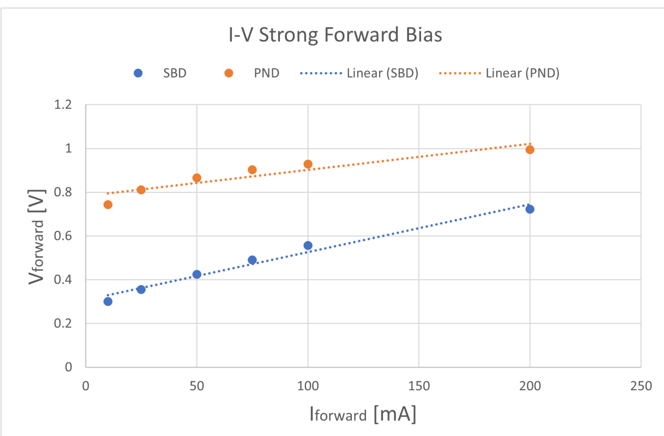

Fig. 8. I-V strong forward bias graph for SBD and PND

With the same circuit setup as in Fig. 6, we tried to set the current to specific values and measured the forward voltage at that current for both the SBD and the PND.

As the currents are now much larger than those in the weak forward bias experiment, we have to consider the effects of r_c and hence we can find the value of r_c from the graph of our results.

$$I_f = I_s e^{\frac{q(V_f - I_f r_c)}{\eta k T}} \tag{3}$$

We can attempt to rearrange Eq.3 into the form y = mx+c:

$$V_f = r_c I_f + \frac{\eta k T}{q} ln(\frac{I_f}{I_s})$$

Notice that there is a logarithm in the y-intercept and hence this is not actually a linear graph however looking at Fig. 8, we can see that the effect of the logarithm is almost negligible and that the line of best fit does approximately fit the curve. Hence r_c is approximately equal to the gradient of the line of best fit. Therefore we get the following results:

SBD $r_c = 2.19\Omega$

PND $r_c = 1.19\Omega$

III. Discussion

A. Semiconductor Analysis

Now that we have found our investigation values we need to check their validity. Our primary aim for CV measurements was to calculate N_D. For comparison we can calculate the atomic number density of silicon using Eq. 4.

$$N = \frac{n}{V} = \frac{\rho N_A}{M} \tag{4}$$

Assuming the density of silicon is $\rho = 2329\text{kg}m^{-3}$, Avogadro's constant is $N_A = 6.02_{10^{23}}$, atomic mass of silicon is $M = 28.09g\text{mol}^{-1}$, then the atomic number density is $N = 4.99_{10^{28}}m^{-3}$ Comparing N_D with the atomic number density, the electron carrier concentration is relatively high for a semiconductor. The magnitude of the doping density $N_D = 2.34_{10^{21}}m^{-3}$ is much greater than the intrinsic carrier concentration of silicon at room temperature $n_i = 10^{16}m^{-3}$. Therefore the electron carrier concentration in the doped silicon is $n \approx N_D$. Using the mass-action law and the charge-balance equation to get a quadratic in p, the hole carrier concentration can be shown to be incomparably small.

This particular N_D is best for a SBD as such a high n-type dopant concentration means that current can flow from the metal to the semiconductor more effectively, but not in the opposite direction hence allowing a much higher forward voltage (hence lower leakage currents and better efficiency), fast switching and a low forward voltage drop.

A suitable dopant material for the n-type doping of silicon is either phosphorus or arsenic as they both have more valence electrons than silicon. Typical metals for making a Schottky contact with n-type silicon include molybdenum, platinum, chromium or tungsten because the metal must be an Ohmic contact. An ideal solution would be gold or platinum however chromium, tungsten and molybdenum are equally suitable for manufacturing purposes and economic benefit.

As an example for the BAT85 SBD cross section in Fig. 9, a reasonable choice of materials would be gold for the metal contacts, a n-type silicon semiconductor for the Schottky contact and chromium for the Ohmic contact.

To make sure a Schottky contact is formed on one side and an Ohmic contact at the other side of the silicon, the work function of the metal must be higher than the work function of the n-type doped semiconductor.

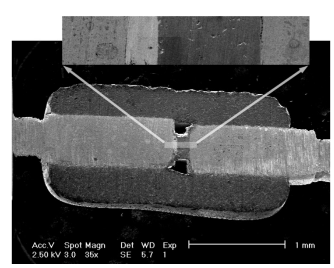

Fig. 9. Cross sectional scanning electron microscopy image of BAT85 SBD

B. *PN Diode Comparison*

There were several notable characteristics of the PND with the main one being a very low saturation current I_s. The forward voltage on the other hand is higher than the SBD for both the weak and strong forward voltage bias. From the CV measurements for a PND, it is possible to see that the doping density is much higher as the saturation current is much lower and remains linear for longer. The contact potential V_0 for the PND is also higher as the PND uses recombination of holes and electrons to function.

$$C = \frac{\epsilon A}{w} \text{ where } w = \sqrt{\frac{2\epsilon(V_0 - V)}{q} \frac{N_A + N_D}{N_A N_D}} \tag{5}$$

Comparing the capacitance equation of the SBD Eq. 1 to the corresponding equation for a one-sided P-N junction Eq. 5, we can see that the capacitance equation for the PND is essentially just a parallel-plate capacitor with the width being the width of the depletion region which varies with the voltage applied (unlike a parallel plate capacitor) . Hence we could work out the acceptor doping density as well as the donor doping density for the PND for a given C-V graph. At a closer analysis, it is possible to see that the two equations for the SBD and PND are very similar where instead the expression N_D for the SBD is replaced with $\dfrac{N_A + N_D}{N_A N_D}$ for the PND.

APPENDIX

1 - C-V MEASUREMENTS

$f_0 = 1781.86kHz$ $C_{10} = 10.4pF$ $f_{10} = 1445.68kHz$
V_0 assumed $0.5V$

Suggested $V_{rev}[V]$	**Measured** $V_{rev}[V]$	$f_r[kHz]$	$(V_0 - V_{rev})^{-\frac{1}{2}}$	$C_{\textbf{SBD}}[pF] = C_0\left((\frac{f_0}{f_r})^2 - 1\right)$
-12	-11.97	1519.263	0.283183	-0.9536
-8	-7.96	1514.838	0.343807	-0.7546
-5	-4.98	1508.648	0.427178	-0.4733
-4	-4.03	1505.380	0.469840	-0.3234
-3	-3.06	1500.440	0.530000	-0.0950
-2	-1.99	1490.920	0.633724	0.3517
-1.5	-1.47	1482.105	0.712471	0.7730
-1	-1.00	1471.004	0.816497	1.3143

TABLE I
F-V MEASUREMENTS AND CAPACITANCE CALCULATIONS

$C_s = -2.25 \pm 0.23pF$
$N_D = 2.34_{10^{21}} m^{-3}$ in the 95 % confidence interval of $[1.87, 2.87]$

2 - I-V MEASUREMENTS

A. *Reverse Bias*

I_s is the reverse saturation current estimated from the graph:
SBD $I_s = -0.3\mu A$
PND $I_s = -0.003\mu A$

V_{rev} **Sug.**	$V_{rev}[V]$ **Meas.**	**SBD** $V_{rev}[mV]$ **Meas.**	**SBD** $I_{rev}[\mu A]$ **Meas.**	V_{rev} **Meas.**	**PND** $V_{rev}[mV]$ **Meas.**	**PND** $I_{rev}[\mu A]$ **Meas.**
–0.25	-0.24	-23.8	-0.238	-0.24	-0.3	-0.003
–0.50	-0.51	-25.6	-0.256	-0.56	-0.4	-0.004
–1.0	-0.97	-27.8	-0.278	-0.98	-0.4	-0.004
–2.0	-2.04	-31.7	-0.317	-2.04	-0.5	-0.005
–4.0	-3.99	-37.2	-0.372	-4.00	-0.5	-0.005
–6.0	-5.99	-42.2	-0.422	-6.03	-0.6	-0.006
–8.0	-8.05	-46.7	-0.467	-8.06	-0.7	-0.007
–10.0	-10.03	-51.0	-0.51	-9.95	-0.7	-0.007
–12.0	-11.98	-55.2	-0.552	-12.0	-0.7	-0.007

TABLE II
I-V MEASUREMENTS IN REVERSE BIAS

B. *Weak Forward Bias*

I_s is the magnitude of the reverse saturation current from Section 2A:
SBD $I_s = 0.3\mu A$
PND $I_s = 0.003\mu A$

SBD $\dfrac{q}{kT} = \dfrac{1.6_{10^{-19}}}{1.38_{10^{-23}} \cdot 298} \approx 38.91$
Gradient $m \approx 36.9011...$

SBD $\eta = \dfrac{q}{kT} \div m = 1.05$ to 3sf

$I_f[\mu A]$	**SBD** $V_f[V]$	$ln[(\frac{I_f}{I_s}) + 1]$	**PND** $V_f[V]$	$ln[(\frac{I_f}{I_s}) + 1]$
5	0.0783	2.871679625	0.357	4.787491743
10	0.0973	3.5361167	0.393	4.882801923
20	0.1144	4.21459369	0.427	4.96517292
50	0.1389	5.121977881	0.47	5.0604831
100	0.1581	5.812138499	0.502	5.125946141
200	0.1763	6.503789047	0.535	5.189246271
500	0.202	7.419180723	0.58	5.269574898
700	0.211	7.755481619	0.597	5.298317367

TABLE III
I-V MEASUREMENTS IN WEAK FORWARD BIAS

Considering three different gradients to give three different R_{Leak}, one for all points (minimum estimate of R_{Leak}), one that excludes points past saturation (medium estimate of R_{Leak}) and one that only consider the first five linear points (maximum estimate of R_{Leak}):
Min (All 9 points) $R_{Leak} = 38.3M\Omega$
Med (Linear 7 points) $R_{Leak} = 40.9M\Omega$
Max (Linear 5 points) $R_{Leak} = 44.7M\Omega$

C. *Strong Forward Bias*

$I_f(mA)$	**SBD** V_f **[V]**	**PND** V_f **[V]**
10.0	0.3	0.744
25.0	0.355	0.811
50.0	0.425	0.866
75.0	0.491	0.902
100.0	0.557	0.928
199.9	0.722	0.994

TABLE IV
I-V MEASUREMENTS IN STRONG FORWARD BIAS

SBD $r_c = 2.19\Omega$
PND $r_c = 1.19\Omega$