Diode Characteristics

Investigating the characteristics of Silicon, Germanium, Zener and Bangor Fabricated Diodes

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This experiment was set up to investigate the different properties and characteristics of several different types of diode. Each diode was investigated by plotting the I-V curve using a Precision Source/Measurement Unit (B2902A) and a Laptop with the corresponding Quick I-V Measurement Software installed.

Upon studying each of the I-V graphs, it was possible to calculate through graphical analysis the cut-in voltage for each of the diodes as well as viewing the breakdown effect of a Zenner diode. Plotting these curves also gave an opportunity to compare the characteristics of a diode produced in the Bangor University lab compared to a mass produced component.

The results of this experiment appear to satisfy the theory behind diodes. The measured cut-in voltage for a Silicon diode was approximately 0.6 volts, and similarly for the Germanium diode 0.2 volts. These are both very close to the expected cut-in voltages. The results also confirm that a Zener diode also had the expected cut-in at 0.6 volts, as well as demonstrating clearly the reverse breakdown effect.

The Bangor fabricated diode had much less defined results. The plotted I-V curves do not have a clear cut-in point and are not as smooth in their nature. They did, however, clearly display that this type of diode is light intensity sensitive.
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The materials used in the production of diodes are semiconductors. A semiconductor in its pure (intrinsic state) is not a good conductor or insulator of electrical current. The most common semiconductors are Silicon and Germanium. These single element semiconductors are characterised by atoms with a valence number 4.

Silicon (and Germanium) has 4 valence electrons. This means in its atomic structure, there are 4 electrons in its outmost energy shell.

As can be seen from Figure 1, the core of the Silicon atom (excluding the valence electrons) has:

- 14 Protons, giving a relative charge of +14
- 10 Electrons, giving a relative charge of -10

The total net change of the core is therefore +4. It is said that the valence electrons experience an attractive force of magnitude +4.

Compare this too Copper, a common conductor.
Similar observation of a Copper atom concludes that it has:

- 29 Protons, giving a relative charge of +29
- 28 Electrons, giving a relative charge of -28

The single valence electron in copper is therefore said to experience an attractive pull of magnitude +1.

From this simple analysis, it is clear that the valence electron in copper can gain enough energy to become a free electron easily, due to the relatively weak attractive force holding it around the atom and because of its large distance from the nucleus. This is why copper is such a good conductor of electrons, as this energy is provided at room temperature.

It is also noted that the valence electrons in Silicon are held to the atom by a much stronger attractive force. At room temperature, only several electrons in an entire Silicon crystal would have enough energy in order to break free from their corresponding atoms to become free electrons. This is why silicon is not a good conductor of electricity.

In a Silicon crystal, each Silicon atom is bonded to 4 others, using the 4 valence electrons in its outer shell. However, there will always be a small number of free electrons, as the lattice is broken down by heat energy. Only at absolute zero (0K) would there be no free electrons.

Semiconductors are known to conduct electrical current in two ways. Electrons that have sufficient thermal energy to break from their atom (free electrons) are known as conduction electrons. As they are free, the easily move through the semiconductor when a potential difference is applied to it. This process in itself is responsible for the second method of electron movement. In the covalent structure, every time an electron escapes to the conduction band, a hole is left in the valence band where it used to be. Electrons in neighbouring covalent bonds can move to nearby holes using a relatively tiny amount of energy. This means that in practise, the holes in the covalent lattice are seen to move in the opposite direction to electron flow. This is known as the hole current.

![Figure 3 Electron and Hole Current in Silicon](image-url)
In a brief comparison, this phenomenon does not occur in Copper as Copper atoms are held together with metallic bonds. The metallic bonds in Copper consist of a sea of positive ions which are surrounded by the delocalised electrons. The electrons move between the positive nuclei holding the atoms together. As all the electrons are delocalised away from the nucleus in this bonding, it accounts for the high conductivity of metals.

**N/P-TYPE SEMICONDUCTORS**

Pure semiconductors are known to be poor conductors. However, their conductivity can be drastically improved by the addition of impurities into the crystal lattice. This controlled addition is known as doping, and increases the number of current carriers available inside the lattice. There are two types of doping practice, both are essential in the production of diodes.

**P-TYPE SEMICONDUCTORS**

This involves doping the pure semiconductor with atoms that have a valence number of 3. This means that the doping atoms only have 3 electrons in their outer shell, so when bonded in the covalent lattice to 4 Silicon (or Germanium) atoms, a hole results, as it does not have enough electrons to complete the bonds. Atoms of this type are called acceptor atoms. These holes do not have a matching free electron in the crystal, therefore this process, in a controlled manor, can be used to increase the number of holes and therefore the conductivity of the semiconductor due to increasing hole current.

In a P-Type semiconductor, holes are the majority electron carriers. There will be a small amount of conduction due to conduction band electrons produced when electron-hole pairs are produced due to the thermal breakdown of the lattice. However, this is a small fraction of the total available carriers. It is worth clarifying that these conduction band electrons are not produced by the doping process.

**N-TYPE SEMICONDUCTORS**

This type of semiconductor is doped with atoms that have a valence number of 5. When these doping atoms are introduced to the semiconductor lattice, they form covalent bonds with 4 adjacent Silicon (or Germanium) atoms. As each bond uses 1 of the valence electrons, there is 1 extra electron. This electron is not involved in the bonding and therefore enters the conduction band. The number of conduction electrons added can be carefully controlled in the doping process. A conduction electron created from the doping process does not have a matching electron hole, as it is provided by the donor atom.

In a N-Type semiconductor, the majority of the current carriers are conduction band electrons introduced by the doping process. A small amount of current will come from holes generated when the lattice has thermal energy to produce electron-hole pairs.
When a semiconductor is doped so that it contains a P-Type region and an N-Type region, a P-N junction forms at the boundary between them. This is a fundamental diode.

The P-Type region has many holes, and the N-Type region has many free electrons. However, both regions are electrically neutral (before the P-N junctions forms), as they have a balanced number of positive charges (protons) and negative charges (electrons).

In any given P-N junction, a depletion region exists between the two doped regions. This is caused by current carrier movements across the junction:

- The N-Type region loses free electrons, as they diffuse across the junction towards the majority holes (like charges repel). This causes a build-up of positive ions on the N-Type side of the junction, due to the imbalance between positive and negative charges.
- The P-Type region loses holes, as the electrons crossing the junction from the N-Type region fill in the spaces. There is therefore more negative charges in the P-Type region than positive, resulting in a layer of negative ions on the P-Type side of the junction.

After the junction has stabilised (does not take long!) an equilibrium is established and there is no further diffusion of electrons across the junction. This is caused by the repulsive force the negative ions of the P-Type region, pushing electrons away from the junction.

At any given time, there is a potential difference across the depletion region known as the barrier potential. This is caused by the layers of positive and negative ions. For current to flow through the P-N junction, a voltage greater than that and of correct polarity, must be applied across the junction to overcome the barrier potential.

Barrier potential in a P-N junction is dependent on a large number of variables including:

- The type of semiconductor material
- The degree of doping in both regions
- The temperature of the junction
Typical barrier potentials are 0.7 volts for Silicon and 0.2 volts for Germanium.

In a diode, the P-Type region is called the anode, and the N-Type region the cathode.

![Diagram to show the terminals of a standard diode](image)

**FORWARD BIAS**

Biasing a diode means applying a DC voltage across it and is described as forward or reverse depending on the polarity of the applied voltage relative to the diode.

![Diagram showing forward biasing of a diode](image)

Figure 6 shows a diode which is being forward biased. The external voltage is $V_{\text{BIAS}}$. The resistor, $R_{\text{LIMIT}}$, is essential in the circuit to limit the current flowing through the diode, preventing it from being damaged by excessive current flow. This circuit fulfills the two criteria for a diode to be forward biased:

- The cathode of the diode (N-Type region) is connected to the negative side of $V_{\text{BIAS}}$.
- The magnitude of $V_{\text{BIAS}}$ is greater than the barrier potential of the diode (assuming the diode is made from Silicon).

As this circuit is correctly forward biased, current will flow around the circuit. An excess of electrons is provided by the negative side of $V_{\text{BIAS}}$ which pushes electrons into the N-Type region of the P-N junction in the diode. As like charges repel, and as they have enough energy, the electrons are able to travel across the depletion zone into the excess of holes in the P-Type region. The electrons do not have enough energy to stay in the conduction band, and therefore fall to the valence band. However, they still have enough energy to travel towards the positive terminal through the holes in the P-Type region. The electrons eventually leave the anode of the diode, flow through the resistor and then return to $V_{\text{BIAS}}$. 
Electrons flowing through the diode in this way cause the size of the depletion region to shrink, as the amount of positive and negative ions at the junction decreases due to electrons being able to cross the barrier.

As energy is required for the electrons to cross the depletion region, this causes a voltage drop across the diode. In Silicon diodes, this is around 0.7V. A small amount of voltage is also lost due to the dynamic resistance of the P/N-Type regions. However, this is so small it can normally be ignored.

**REVERSE BIAS**

Reverse bias is the condition that prevents current from flowing backwards through a diode.

![Diagram showing a diode that has been reverse biased](image)

As you can see from Figure 7 above, the only difference between the forward and reverse bias circuits shown here is the polarity of the power supply. It is worth noting that for this circuit $R_{\text{LIMIT}}$ is irrelevant because almost no current flows.

Current is prevented from flowing because the depletion region (and therefore the barrier potential) in the diode grows. This is because the excess electrons in the electron rich N-Type region are pulled away from the P-N junction towards the positive side of $V_{\text{BIAS}}$. This causes an increase in the number of positive ions in the N-Type region. The few electrons that are in the P-Type region (created by thermal breakdown) travel towards the N-Type region, and are able to cross the junction as they are in the conduction band. They are then able to travel through the small number of holes in the N-Type region towards the positive terminal. This amounts to a tiny current known as the reverse bias current.

There will be a point, if $V_{\text{BIAS}}$ is large enough, that the diode will breakdown and allow current to flow. This normally causes permanent damage to the diode so it not recommended. The current flow is caused by the free minority electrons in the P-Type region being accelerated due to the large potential difference across the diode. They travel at high speed (high energy) towards the depletion region, colliding with other electrons in the valence band and providing them with sufficient energy to enter the conduction band. These electrons cross the depletion region and have enough energy to travel through the N-Type region as conduction electrons. High energy electrons can knock more than one other
electron into the conduction band thereby creating an avalanche effect, increasing current dramatically.

**ZENER DIODES**

Zener diodes are Silicon P-N junction diodes designed to act as a normal diode but also to allow a controlled reverse breakdown. Figure 8, below, shows the circuit symbol for a Zener diode.

![Figure 8 Circuit symbol for a Zener Diode](image)

Zener diodes are much heavier doped than regular diodes, giving rise to a much smaller depletion region. There are two different types of Zener diodes:

- **Zener breakdown (low reverse voltages)** – Allows reverse current due to the very intense electric field that exists in the very narrow depletion region which is strong enough to pull electrons from the valence band into the conduction band.
- **Avalanche breakdown (high reverse voltages)** – Have the same properties as Zener breakdown diodes, but the avalanche effect as in a standard diode has much greater effect.
THEORETICAL

THE VOLTAGE-CURRENT CHARACTERISTIC

Theory indicates that for a p-n junction, the current $I$ is related to the voltage $V$ by the equation

$$ I = I_0 \left( e^{V/nV_T} - 1 \right) $$

(1)

A positive value of $I$ means that current flows from the p to the n side. The diode is forward biased if $V$ is positive, indicating that the p side of the junction is positive with respect to the n side. The symbol $n$ is unity for germanium and is approximately 2 for silicon at rated current. $I_0$ is the saturation current under reverse bias.

The symbol $V_T$ stands for the volt equivalent of temperature, and is given by

$$ V_T \equiv \frac{T}{11,600} $$

(2)

At room temperature ($T = 300K$), $V_T = 26mV$. [6]
EXPERIMENTAL

AIMS

The aims of this experiment are to:

- Become familiar with the operation of a B2902A Agilent Precision Source/Measure Unit.
- Measure the Current-Voltage characteristics of:
  1. A 100 ohm resistor (for reference)
  2. A silicon diode (IN4004)
  3. A germanium diode (OA90)
  4. A Zener diode (BZX)
  5. A Bangor University fabricated diode.

Plotting the graphs for these characteristics will allow the cut-in voltages to be measured for each diode.

- View the breakdown effect of a Zener diode.
- Study how light intensity affects the Current-Voltage characteristic of the Bangor University fabricated diode.

EQUIPMENT

- B2902A Agilent Precision Source/Measure Unit
  - Minimum measurement resolution: 100 fA/100 nV
  - Max sample rate: 50000 pts/s [7]
- Samsung RV520 Laptop for data logging, connected by USB2.0
- Quick I-V Measurement Software
- Clips for attaching standard diodes to Measurement Unit
- Accurate pin point system for attaching Bangor diodes to the Measurement Unit.
PROCEDURE

FAMILIARISATION

- The resistor was connected to the Measurement Unit with the clips.
- Everything was checked to make sure it was connected correctly.
- The Quick I-V Measurement Software was loaded and configured.
  - Start voltage -2V
  - Stop voltage +2V
  - Increment 200 steps
- The test was then run. The software automatically takes readings (to 8 decimal places) using the Measurement Unit and plots the I-V graph.

SILICON AND GERMANIUM DIODES

- Each connected in turn to the Measurement Unit with the clips.
- Everything was checked to make sure it was connected correctly (diode the correct way round).
- Test was run with same configuration as with the resistor.
- I-V graphs plotted.

ZENER DIODE

- Connected to the Measurement Unit with the clips.
- Everything was checked to make sure it was connected correctly (diode the correct way round).
- The Quick I-V Measurement Software was configured as follows:
  - Start voltage -12V
  - Stop voltage +2V
  - Increment 200 Steps
- Test was run and the I-V graph plotted.

BANGOR FABRICATED DIODE

- Diode was cleaned using some cleaning paper.
- Connected to the Measurement Unit via a highly accurate pin point system. (Pin touches aluminium contact [anode], metal base underneath diode [cathode])
- Everything was checked to make sure it was connected correctly (diode the correct way round).
- The Quick I-V Measurement Software was configured as follows:
  - Start voltage -2V
Diode Characteristics

- Stop voltage +2V
- Increment 200 steps

- Test was run and the I-V graph plotted.
- The procedure above was then repeated with the diode in the dark covered by a cardboard box.
- The procedure above was then repeated with the diode have a very bright light directed at it.
As expected the resistor produced a linear graph. We can verify the graph is correct by calculating the resistance of the resistor using ohms law

\[ V = IR \]

\[ R = \frac{V}{I} \]

\[ \frac{1}{R} = \frac{I}{V} \]

(3)

Therefore, the gradient \( \frac{I}{V} \) is equal to \( \frac{1}{R} \)

\[ \frac{1}{R} = \frac{0.02 - (-0.02)}{2 - (-2)} \]

\[ R = 100 \text{ ohms} \]
The graph above shows the I-V characteristic for the silicon diode. As expected, it is a straight line, of 0 current, up until the cut-in voltage, where it increases rapidly. Calculated from the above graph using computer software, the cut-in voltage is 0.668v (+/- 0.00909v).

*See Appendix for information on how this was calculated.*
GERMANIUM DIODE

This graph shows the measured I-V characteristic for the Germanium diode. It too shows a linear relationship between current and voltage up until the cut-in voltage. After this the current increases rapidly, as it flows through the diode. The cut-in voltage, measured by computer software, is 0.183v (+/- 0.015874v).

See Appendix for information on how this was calculated.
This I-V graph of the Zener diode shows both forward bias and reverse bias cut-in voltages. Using computer software, the forward bias cut-in voltage was 0.673v (+/-0.0364v). The reverse breakdown voltage was -10.182v (+/- 0.0364). This is the expected shape of the graph, although the reverse breakdown voltage was not a smooth curve, most likely due to experimental error. Unlike the other diodes, the current in the Zener diode appear to increase linearly after the cut-in voltages.

See Appendix for information on how this was calculated.
Many thanks to Alex Hoosen, Andy Rosser and Luke Allen for the experimental results for this diode.

This graph shows the forward bias-cut in voltage for the supplied Bangor diode very clearly. Instead of using the Quick I-V Measurement Software to plot this graph, the raw values were taken and transferred to Microsoft Excel 2010 [9], to allow all 3 curves to be plotted on the same graph. Careful analysis of the graph and the raw data suggests that the cut-in voltages for the diode is 0.623v (+/- 0.02v).

The graph also shows that there must be a relationship between light intensity and current flow (above the cut-in voltage), which will be discussed in the discussion section.
DISCUSSION

RESISTOR

The experimental results from this experiment back up the well-known theory that resistors are ohmic components at a constant temperature. The perfectly straight line provided by the I-V graph proves that in this instance, the relationship between current and voltage is linear and therefore purely resistive. Also, as the voltage was increased in small steps and each measurement taken quickly, heating effect of the resistor must have been minimal. This verifies ohms law is correct.

\[ V = IR \]  

Doing this component first means that it is certain the experimental equipment was set up correctly and as the value of resistance calculated from the graph matches the value of the resistor provided, there have not been any noticeable errors created by the measurement apparatus.
The results from the Silicon diode also support the theory behind its design. No current is able to pass through it until the voltage across it exceeds the barrier potential of the P-N junction. The expected value of the barrier potential for a Silicon diode is always approximately 0.7v. From the results in this experiment, the barrier potential was measured as 0.668v meaning a percentage error of around 4.8%. This error could be caused by a number of different components and environmental factors during the experiment, such as unaccounted resistance of the wires connecting the diode to the Measurement Unit and also the temperature of the surroundings.

From the graph it can be seen that after the cut-in voltage calculated, the current increases very rapidly, as electrons have enough energy to cross the P-N junction. However, the voltage also continues to increase very slightly, and this is due to the internal dynamic resistance of the semi conductive material. This means that above this point, the diode also has resistance properties that need to be accounted for.

\[ r'_d = \frac{\Delta V_F}{\Delta I_F} \]  

(4)

The graph shows that Silicon diodes have a relatively small internal dynamic resistance as the current change after the cut-in voltage is much larger than the voltage change.
GERMANIUM DIODE

The results for the Germanium diode are somewhat similar to the Silicon diode, and yet somewhat different. The Germanium diode also does not allow any current to pass through it until its barrier potential is reached. The barrier potential in Germanium diodes is expected to be around 0.2v. In this experiment the measured cut-in voltage (and therefore the barrier potential) was measured to be 0.183v giving an approximate error of 9.3%, most likely caused by the same factors as had influenced the Silicon diode results, as they both show lower values here than expected.

It is worth noting here the difference in the barrier potentials between the materials. Germanium has a much lower barrier potential than Silicon. This is due to the increased distance that the valence electrons in Germanium are away from the strong positive pull of the nucleus. This therefore means that it takes much less energy for an electron in a germanium diode to jump from the valence to the conduction band.

From the graph it can also be seen that after the barrier potential has been exceeded, the current increases slower (at a lower gradient) than in the Silicon diode. This shows that Germanium diodes have a high internal dynamic resistance, as more voltage is lost as current increases.
ZENER DIODE

Zener diodes have the interesting characteristic that they can work in an almost identical fashion to a standard Silicon diode when forward biased, but also can be used in the reverse-breakdown region without damaging the diode.

In this experiment the forward cut-in voltage for the diode was measured to be 0.673v which is very similar to the value recorded by the Silicon diode. This result has an associated percentage error of approximately 4%.

The reverse breakdown region of the diode is where the results get interesting. The Zener diode has a clearly defined breakdown voltage, in this experiment measured as -10.182v. The rating of the diode was -10v giving a percentage error of 1.8%. This effect is very useful, as from diode theory we know that when the reverse breakdown voltage is reached, the voltage remains almost constant as the current increases dramatically (due to the very low internal dynamic resistance). It is worth noting that the reverse breakdown voltages of Zener diodes are designed to be much lower than the reverse breakdown voltages of regular Silicon diodes to allow engineers to take advantage of this effect.

As relatively low breakdown voltages have been used in this experiment, the breakdown effect in the diode is predominantly Zener breakdown, which allows reverse current due to the very intense electric field that exists in the very narrow depletion region which is strong enough to pull electrons from the valence band into the conduction band and not avalanche breakdown as in normal diodes.
BANGOR FABRICATED DIODE

Using the Bangor fabricated diode allowed some other properties of diodes to be displayed. As the Bangor diodes are made from Silicon, it would be expected the cut-in voltage to be approximately 0.7. However, the measured cut-in voltage was lower, only around 0.623v giving a percentage error of 12.4%. This is most likely caused due to impurities in the diode which contaminated it during manufacture. Also, as the contacts needed to connect the diode to the measurement unit where metallic pins/plates, a boundary resistance will have been introduced as well as normal wire resistance.

The graph of results shows that dynamic internal resistance of the diode is highly dependent on the light intensity of the surroundings. Having a high value of light intensity allows much greater current to flow through the diode than in the dark at a given voltage. This can be explained using wave-particle duality theory and the photo-electric effect.

It can be assumed that light exists of photons, and therefore in this experiment, the higher the light intensity the more photons hit the diode. When a photon hits the silicon, there is a small chance that it will provide a valance electron with sufficient energy to enter the conduction band. Therefore, it would make logical sense to assume that as more electrons are entering the conduction band, the resistance is lowered and more current can flow.

Using equation (1), it is possible to calculate the saturation current under reverse bias for the Bangor diode:

\[ I = I_0 \left( e^{\frac{V}{nVT}} - 1 \right) \]

From the results, when \( V = 1.75 \text{v} \), \( I = 2.07 \text{mA} \)

Therefore \( I_0 \) can be calculated as \( 5.01 \times 10^{-18} \text{A} \)
CONCLUSIONS

The results of this experiment show why diodes are such a critical component in designing circuits. They have the ability to not only stop current flowing in the wrong direction (within reasonable voltages) but also to control the current flowing in the correct direction, as even in forward bias the current flow is voltage controlled.

It is displayed clearly that all diodes have associated cut-in voltages which are dependent on a large number of variables, however, mainly temperature, material and degree of doping. It has been shown that Germanium diodes have a much lower cut-in voltage than Silicon diodes because of Germaniums atomic structure.

From theory, it is known that all diodes have a reverse saturation current caused by the minority charge carriers in each region of the P-N junction. The calculation using results from the Bangor diode shows that this current is normally very small and can be ignored in the vast majority of circumstances.

All real diodes have a dynamic internal resistance due to the resistance of the material they are made from. If they did not (an ideal diode) then the current flow could be of an infinite value as soon as the voltage was higher than the barrier potential. The results show that Germanium diodes have a higher internal resistance than Silicon diodes and this is caused by Germanium atoms increased nucleus size.

Zener diodes are a special type of P-N Silicon diode that can be used for controlled reverse breakdown, and it will not damage the diode. This is possible due to very accurately defined doping in the material, giving rise to a very small depletion region allowing Zener breakdown to take place.

The Bangor diode shows that diodes can be made light intensity sensitive, as photons are able to excite the electrons in the diode (similar to increasing temperature), giving rise to an increase in electrons that have sufficient energy to jump from the valance band to the conduction band.

Finally, all diodes have a reverse breakdown voltage at such point current will flow backwards through the diode. This is due to the avalanche effect, as electrons are accelerated due to the large potential difference, and at high speed knock other electrons into the conduction band. This normally damages the diode, if they are not designed to have this effect.
ACKNOWLEDGEMENTS

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(3) My partners in Electronics Lab, Mr Peter Adams and Mr Mathew Clewlow.

(4) Mr Alex Hoosen, Mr Andy Rosser and Mr Luke Allen for their Bangor Diode results.
REFERENCES

Figure [1] - http://www.chemicalelements.com/elements/si.html


Figure [3] - http://hyperphysics.phy-astr.gsu.edu/hbase/solids/intrin.html


APPENDIX

FORMULAE

RECTIFIERS

(1) \[ I = I_0 \left( e^{V/nV_T} - 1 \right) \]

(2) \[ V_T \equiv \frac{T}{11,600} \]

OHMS LAW

(3) \[ \frac{1}{R} = \frac{I}{V} \]

DYNAMIC RESISTANCE

(4) \[ r'_d = \frac{\Delta V_F}{\Delta I_F} \]
SOFTWARE

The cut-in and breakdown voltages of the diodes used in this experiment were calculated manually using the graphics produced by the Quick I-V Measurement Software.

Using the GNU Image Manipulation Program (GIMP) [8], it is possible to zoom into the graphics at a pixel scale. Using this high, it enabled the following to be completed on each graph:

- The cut-in (or breakdown) point on each curve was zoomed in to the pixel level.
- A point was placed on the line at this point.
- Using the straight line tool, a perfectly straight line can be drawn from this point to both axes.
- Using the measurement tool, we can measure accurately how many pixels each division on the graph scale is represented by.
- The voltage increase per pixel is then calculated by
  \[ \text{Voltage per pixel} = \frac{\text{Division Size}}{\text{Number of pixels}} \]
- The distance between the cut-in line and the nearest graph scale division is then measured.
- The voltage increase for that distance is calculated by
  \[ \text{Voltage increase} = \text{Voltage per pixel} \times \text{Number of pixels} \]
- This is then added to the nearest scale division to give the value of where the cut-in line crosses the x-axis.

As we are measuring values to the nearest pixel, the error for each reading is +/- 1 pixel. As we take 2 measurements in each calculation, the error in the voltage reading is

\[ +/- 2 \times \text{Voltage per pixel} \]

As this is always significantly larger than the error produced by the B2902A Agilent Precision Source/Measure Unit, the error introduced by the equipment can safely be ignored.