EE236 Experiment 2 : Supporting Document

Schottky Diode

The Schottky diode, also known as Schottky barrier diode or hot-carrier diode, is a semiconductor diode formed between a metal and a semiconductor, creating a Schottky barrier (instead of a semiconductor–semiconductor junction as in conventional diodes).

Typical metals used are molybdenum, platinum, chromium or tungsten, and certain silicides (e.g., palladium silicide and platinum silicide), whereas the semiconductor would typically be n-type silicon.

The metal side acts as the anode, and n-type semiconductor acts as the cathode of the diode; meaning conventional current can flow from the metal side to the semiconductor side, but not in the opposite direction.

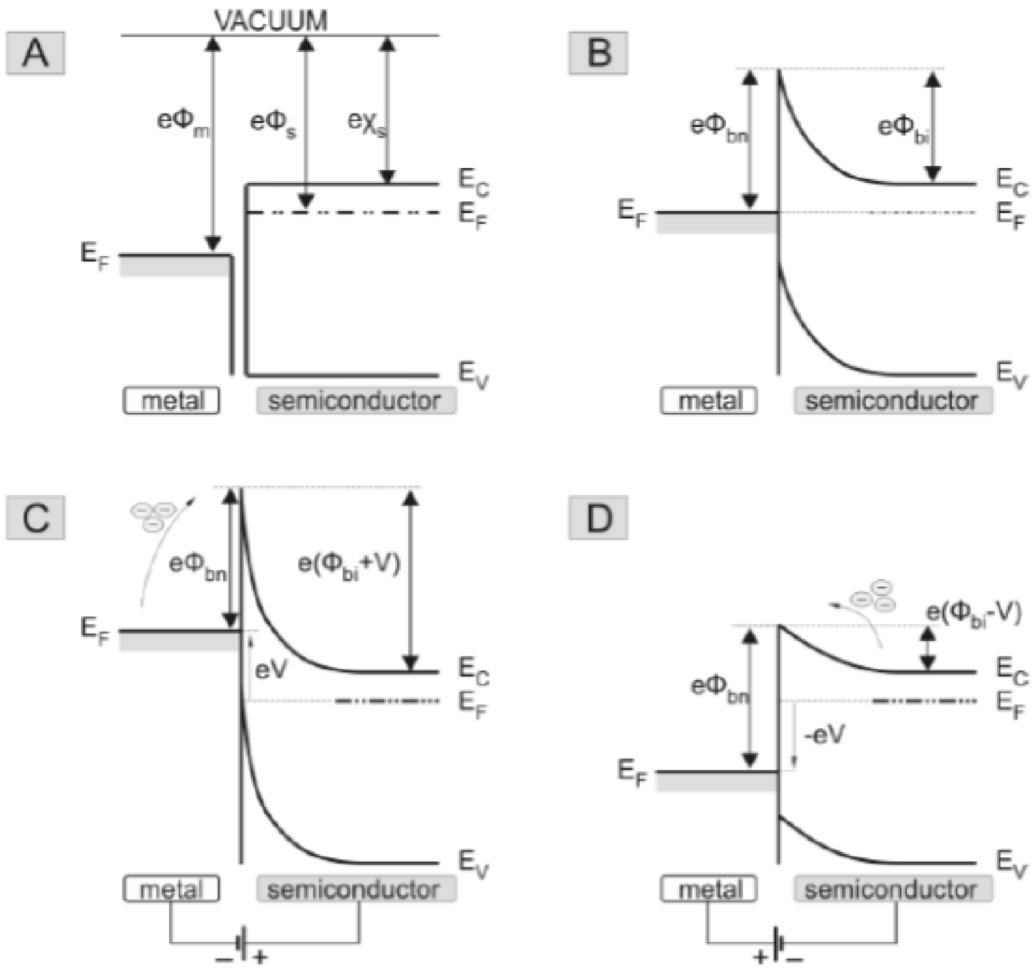
The choice of thecombination of the metal and semiconductor determines the forward voltage of the diode. Both n- and p-type semiconductors can develop Schottky barriers. However, the p-type typically has a much lower forward voltage.

Symbol of Schottky Diode

Construction

As soon as these metal and semiconductor are brought into contact and thermal equilibrium is established, their Fermi levels become equal. Electrons from the semiconductor lower their energy level by flowing into the metal. Charge accumulates at the interface, distorting the energy bands in the semiconductor. This creates an energy barrier, known as the Schottky barrier, which prevents more electrons from flowing from the n-type material into the metal without assistance from an external energy source of the correct polarity to elevate their energy above that of the Schottky barrier height. External energy of the opposite polarity increases the barrier height, thus preventing conduction. When metal is brought into contact with an n-type semiconductor during fabrication of the chip, electrons diffuse out of the semiconductor into the metal, leaving a region known as the “depletion layer” under the contact that has no free electrons. This region contains donor atoms that are positively charged because each lost its excess electron. This charge makes the semiconductor positive with respect to the metal. Diffusion continues until the semiconductor is so positive with respect to the metal that no more electrons can go into the metal. The internal voltage difference between the metal and the semiconductor is called the contact potential, and is usually in the range 0.3 – 0.6 V for typical Schottky diodes.

When a positive voltage is applied to the metal, the internal voltage is reduced, and electrons can flow into the metal. Only those electrons whose thermal energy happens to be many times the average can escape, and these “hot electrons” account for all the forward current from the semiconductor into the metal.



Energy band diagrams for Shottky contact on n-type semiconductor:

A. Before contacting
B. After contacting, in equilibrium
C. Under Reverse bais
D. Under Forward bias

The barrier between the metal and the semiconductor can be identified on an energy band diagram. To construct such diagram we first consider the energy band diagram of the metal and the semiconductor, and align them using the same vacuum level as shown in Figure (a). As the metal and semiconductor are brought together, the Fermi energies of the metal and the semiconductor do not change right away. This yields the flat band diagram of Figure (b).

The barrier height, Φ_B, is defined as the potential difference between the Fermi energy of the metal and the band edge where the majority carriers reside.

From Figure (b), it can be noted that for an n-type semiconductor the barrier height is obtained from:

$$\Phi_B = \Phi_M - \chi$$

For p-type material, the barrier height is given by the difference between the valence band edge and the Fermi energy in the metal:

$$\Phi_B = E_g/q - \Phi_M + \chi$$

A metal-semiconductor junction will therefore form a barrier for electrons and holes if the Fermi energy of the metal as drawn on the flat band diagram is somewhere between the conduction and valence band edge.

In addition, we define the built-in potential, Φ_I, as the difference between the Fermi energy of the metal and that of the semiconductor.

$$\Phi_I = \Phi_M - \chi - (E_c – E_{fn})/q \qquad \text{[for n-type]}$$

$$\Phi_I = \chi + (E_c – E_{fp})/q - \Phi_M \qquad \text{[for p-type]}$$

The flat band diagram, shown in Figure (b), is not a thermal equilibrium diagram, since the Fermi energy in the metal differs from that in the semiconductor. Electrons in the n-type semiconductor can lower their energy by traversing the junction. As the electrons leave the semiconductor, a positive charge, due to the ionized donor atoms, stays behind. This charge creates a negative field and lowers the band edges of the semiconductor. Electrons flow into the metal until equilibrium is reached between the diffusion of electrons from the semiconductor into the metal and the drift of electrons caused by the field created by the ionized impurity atoms. This equilibrium is characterized by a constant Fermi energy throughout the structure.

Operation of a metal-semiconductor junction under forward and reverse bias is illustrated with Figure (c) and (d). As a positive bias is applied to the metal (Figure (c)), the Fermi energy of the metal is lowered with respect to the Fermi energy in the semiconductor. This results in a smaller potential drop across the semiconductor. The balance between diffusion and drift is disturbed and more electrons will diffuse towards the metal than the number drifting into the semiconductor. This leads to a positive current through the junction at a voltage comparable to the built-in potential.

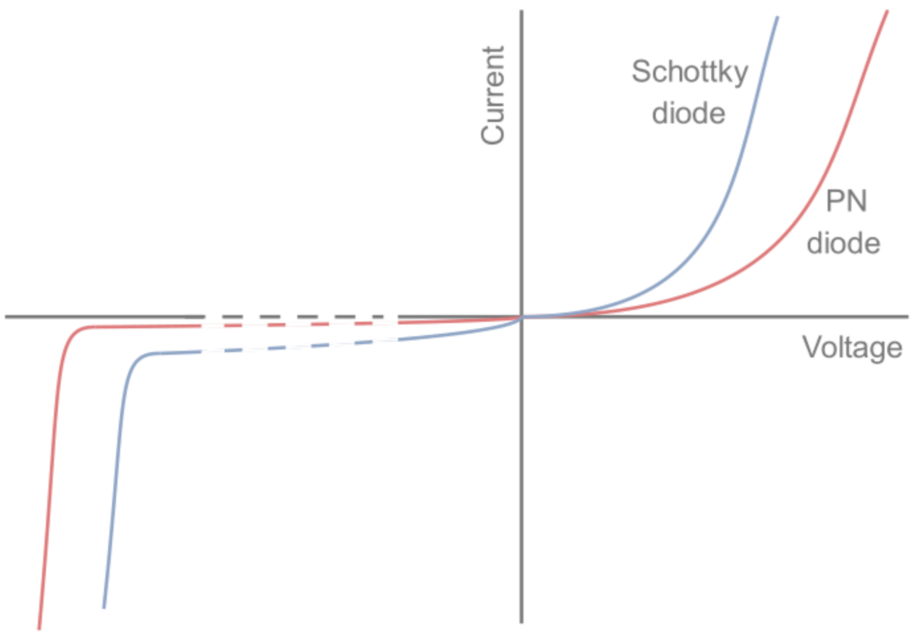
As a negative voltage is applied (Figure (d)), the Fermi energy of the metal is raised with respect to the Fermi energy in the semiconductor. The potential across the semiconductor now increases, yielding a larger depletion region and a larger electric field at the interface. The barrier, which restricts the electrons to the metal, is unchanged so that the flow of electrons is limited by that barrier independent of the applied voltage. The metal-semiconductor junction with positive barrier height has therefore a pronounced rectifying behaviour. A large current exists under forward bias, while almost no current exists under reverse bias.

The potential across the semiconductor therefore equals the built-in potential, Φ_I, minus the applied voltage, V_a.

$$\Phi(x = \infty) - \Phi(x = 0) = \Phi_i - V_a$$

Schottky diode I-V characteristics

The I-V characteristic is shown below. In the forward direction the current rises exponentially, having a knee or turn on voltage of around 0.3 V. In the reverse direction, there is a greater level of reverse current than that experienced using a more conventional PN junction diode.



I-V characteristics of Schottky Diode

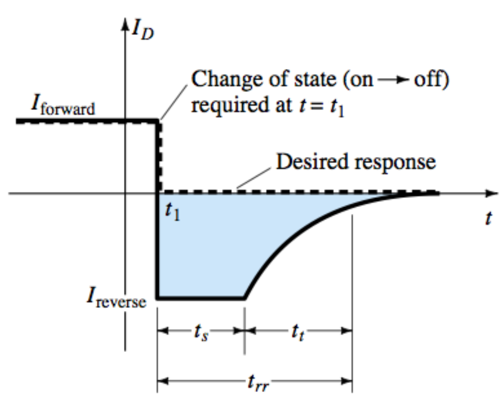
Additionally the reverse breakdown voltage is also typically lower than an equivalent silicon PN junction diode.

Reverse Recovery Time

Ideally, a diode is:

1. a perfect conductor when it is forward biased
2. a perfect insulator when reverse biased, and
3. the transition from conductor to insulator is instantaneous upon a forward bias/reverse bias switch.

Practical diodes don't display these ideal characteristics, and the question is related to the transition (switching) time from conduction to open circuit when the bias is reversed. The figure below shows what happens when the diode bias is switched from forward to reverse. At the switch time, the current reverses and stays at a constant level for a period of time called the storage time, ts. During this time the diode acts essentially as a short circuit. Then the current decreases to the reverse leakage current value. This latter time is called the transition time.



The sum of the storage and transition times is the reverse recovery time. It depends on the forward current, and data sheets give the reverse recovery time along with the test conditions.

Why does a diode behave this way?

When PN junction is forward biased, a large number of electrons are injected into the p-material, and a large number of holes are injected into the n-material of the PN junction. When the diode is then reverse biased, these stored minority carriers must return to the opposite material. The time it takes for the electrons to move from the p-material back to the n-material and the holes to move from the n-material to the p-material is the storage time, and is determined by the geometry of the PN junction. Once this migration is complete, the electrons diffuse to, and recombine at the anode, and the holes diffuse to and recombine at the cathode until there are no more of the original stored carriers left. This time is the transition time, and is determined by the geometry and doping levels of the p- and n-materials.

The reverse recovery times for PN junction diodes are a few microseconds for general-purpose rectifier diodes such as the 1N4001. When a diode is employed to rectify a 60-Hz voltage in a power supply, a reverse recovery time of 1 microsecond is irrelevant. However, when the diode is used as a switch in a circuit that runs at 100 KHz, then 1 microsecond is a substantial part of the conduction cycle, and the diode will dissipate a lot of energy. In switching applications such as DC-DC converters this can seriously impact efficiency. By manipulating doping levels and junction geometry one can manufacture semiconductor junction rectifiers with much smaller reverse recovery times. For example, the industry standard 1N4933 fast rectifier has a reverse recovery time of 200 ns. For small-signal (as opposed to power rectification) applications PN junction diodes can be made quite fast-the widely used 1N4148 small-signal diode has a reverse recovery time of 4 ns. However, all PN junctions have by necessity stored minority carriers when forward biased, so there are limits on what can be done. Additionally, the faster speed comes at the expense of higher forward voltage drop and higher reverse leakage currents.

For really small switching times, Schottky barrier diodes are used. These diodes are not PN junctions, but consist of a semiconductor-metal junction, and there are no stored minority carriers. Switching times can be as small as a few hundred picoseconds. This is very useful when protecting MOS devices, and in lower level switching and steering applications. Apart from fast switching times, Schottky diodes also have the desirable quality of low forward voltages. This makes them attractive for power rectifier applications