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Walter Schottky

born July 23, 1886, Zürich, Switzerland
died March 4, 1976, Pretzfeld, W.Germany

German physicist whose research in solid-state physics and electronics yielded many effects and devices that now bear his name (Schottky effect, Schottky barrier, Schottky diod).

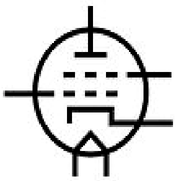
In today's electrical engineering community the word "Schottky" has been transformed from a man's name into a technical term associated with the construction of a wide range of electronic components. This is not an honor shared only by Walter Schottky, but it is perhaps a mark of respect that is greater than the traditional medals, awards, and other prestigious recognitions that reward success. Through is his life and career Schottky permanently embedded his name into an industry that he so diligently contributed to and quietly revolutionized.

Walter Schottky was born on July 23, 1886 in Zurich, Switzerland, but he spent his life in Germany. His father, Friedrich, was a university mathematician. As a result of his career move from Marburg to Berlin, Schottky attended schools in both places and entered the Humboldt University in Berlin in 1904, where he studied physics. In 1912, he was awarded a doctorate in Berlin for his thesis on the Special Theory of Relativity, which Albert Einstein had announced only seven years earlier. Schottky's tutor was Max Planck, the originator of the Quantum Theory and a man at the heart of modern physics. After receiving his Ph.D., Schottky moved to Jena, Germany, where he worked under Max Wien. It was here that he turned away from relativity theory and began what would become his life's work—the interaction of electrons and ions in vacuum and solid bodies.

For the next fifteen years his career consisted of movements between university and industrial research. He began with a couple of years with Max Wien at Jena, after which he joined the Siemens industrial research laboratories in Berlin, staying there until 1919. In 1920 he returned to the university, where he worked under Wilhelm Wien at Wurzburg. It was at Wurzburg where he became qualified as a university lecturer. Wilhelm Wien is chiefly remembered for his work on black-body radiation, for which he received the Nobel Prize in Physics in 1911. After three years with W. Wien, Schottky advanced his academic career by becoming the Professor of Theoretical Physics at Rostock. At the age of 41 he moved for the last time back to industrial research, rejoining Siemens AG. He remained at Siemens until his retirement in 1958.

Schottky's achievements can be divided into two phases: the first being research into vacuum electronics and the second, starting in 1929, covering semiconductor electronics. There were,

however, two other accomplishments that do not fall under these two areas that would alone have guaranteed him a place in history. These two inventions were the ribbon microphone and the superhet. The ribbon microphone was invented jointly with Erwin Gerlach in 1924. It consisted of an extremely thin concertina ribbon of aluminum placed between the poles of a permanent magnet. They also invented a ribbon loudspeaker as well, simply by reversing the physical effects of the microphone. The invention of the superhet is typically credited to Edwin Armstrong, but Schottky independently discovered the same principle of the superheterodyne with IF amplification in 1918. (*Superheterodyne receiver: Radio receiver that converts all radio frequencies to a fixed intermediate frequency to maximize gain and bandwidth before demodulation.*)
Schottky began his work on electron physics at Jena, where he performed theoretical and experimental studies of the space charge effects of electrons emitted from cathodes in vacuum tubes. In 1913 he independently discovered the basic law relating current in a valve to the applied voltage, or what is now known as the "Three-halves law".



At Siemens, Schottky further developed his interests in electronic valves. Although he was only there from 1915 to 1919, he was able to produce a number of discoveries and inventions. He invented the screen-grid tube in 1915, and in 1919 he invented the tetrode, the first multigrid vacuum tube. A tetrode contains two grids--the basic one and a second grid called the screen. The screen prevents the tube from producing unwanted oscillations

He soon overshadowed that great achievement with his prediction of thermal and shot noise, which are two of the fundamental classes of noises in electronic devices. Walter Schottky discovered the random noise due to the irregular arrival of electrons at the anode of thermionic tubes that is called "shot noise" (Schottky effect) in 1914 while studying under Planck in Berlin.

In the early years of electronic circuitry engineers and physicists were trying to solve problems involved in making better vacuum valves. Although many of the problems were related to design and manufacturing techniques, such as inadequate vacuum pumping, mechanical resonance, and poor welds, the fundamental problem of noise was gaining recognition. Scientists were trying to discover what the ideal performance of valve amplifiers would be once all the manufacturing problems were eliminated, which would then isolate the fundamental problems of physics. J.B. Johnson and Harry Nyquist, who worked at Bell laboratories in the United States, would provide some of the answers to these problems in the 1920's. Walter Schottky, however, had already answered most of these problems in his classic paper on noise in valve amplifiers, which was published in 1918. He had reached the conclusion that there would be two sources of noise of a fundamental nature in an amplifier. The first would occur in the input circuit and would result from the random motion of charge caused by the thermal motion of the molecules in the conductors, or what is now known as thermal noise. Since the noise is originated in the input circuit and would appear amplified in the output circuit, he deduced that it would be proportional to the Boltzmann constant (k) multiplied by the absolute temperature. In the mid-1920's, Johnson experimentally identified thermal noise and Nyquist analyzed the discovery mathematically, producing a formula of 4kT watts per unit of bandwidth, confirming Schottky's deduction. Schottky's second fundamental source of noise would be caused by the randomness of the emission from the cathode and the randomness of the velocity of the emitted electrons, which is now know as shot noise. This noise was first experimentally identified and measured in Schottky's laboratory. Later studies showed it was linked to factors such as the material and design of the cathode. Schottky was able to create a better understanding of the sources of these noises, which led to better valves and would also be of benefit to the next period of his career, the semiconductor age.

The next great period of his work was to be with semiconductors, but he would direct his attention to thermodynamics before actually working with them. Throughout the 1920's Schottky gathered material, which eventually appeared in 1929 in his book on thermodynamics, *Thermodynamik*. It presented the thermodynamic theory of solids with very low impurity content or with small deviations from stoichiometry. He was one of the first to point out the existence of electron “holes” in the valence-band structure of semiconductors. In 1935 he noticed that a vacancy in a crystal lattice results when an ion from that site is displaced to the crystal's surface, a type of lattice vacancy now known as the Schottky defect. These studies are what led him to the study of semiconductors, which is considered the most important part of his career. Ferdinand Braun is usually credited with the first systematic study of metal-semiconductor rectifiers, work that was published in 1874. Point-contact metal-semiconductor rectifiers were used in the early 1900's, but it was not until 1931 that the theory of current flow was produced by A.H. Wilson. Schottky published his diffusion theory of current transport in metal-semiconductor junctions approximately seven years later.

In 1938 he created a theory that explained the rectifying behaviour of a metal-semiconductor contact as dependent on a barrier layer at the surface of contact between the two materials. The metal semiconductor diodes later built on the basis of this theory are called Schottky barrier diodes. The importance of these diodes is due to the speed at which they can be switched off from the saturated state. This speed is enabled by the fact that they are made from a junction between a metal and a semiconductor instead of a junction between two pieces of a semiconductor. Schottky also discovered that the current emitted from the metal cathode into the vacuum depends on the metal's work function, and that this function was lowered from its normal value by the presence of image forces and by the electric field at the cathode. This effect later became known as the Schottky effect, and would later be extended to semiconductor devices to revolutionize their construction. Schottky would continue to produce predictions and inventions that would transform the field of electronics until his retirement in 1958.

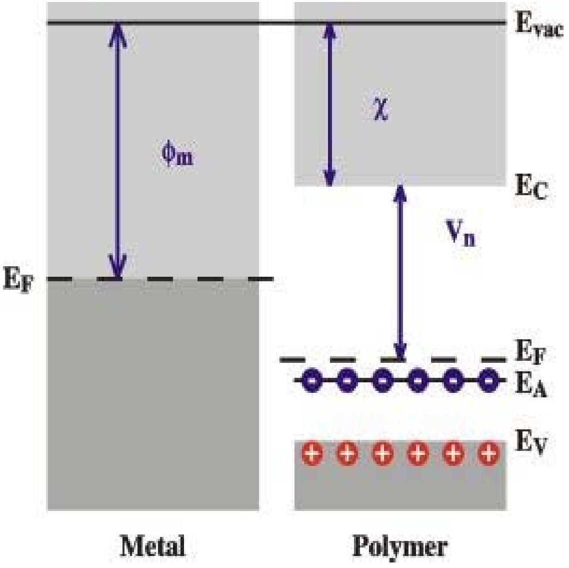
He spent the rest of his life in Pretzfeld, Germany, where he died on March 4, 1976 at the age of 90. His death came just two years after his former employer, Siemens, had begun commercially manufacturing Schottky diodes for microwave use. Although he was known as "a modest and selfless character who avoided the center stage," Walter Schottky humbly changed the industry that controls almost every aspect of modern daily life.

References

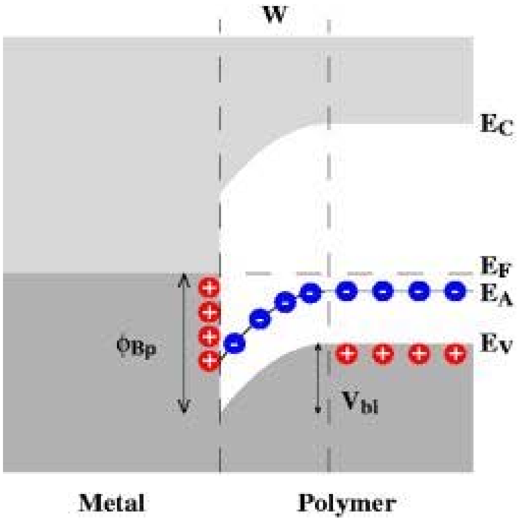
1. Johnson, J.B. "Electronic noise, the first two decades," *IEEE Spectrum*, February, **1971**.
2. Fagen, M.D. (Ed). "*A History of Engineering and Science in the Bell System*," Vol 1, Bell Labs, **1975**.
3. Welker, H. *Solid State Electronics*, Vol 19, pp. 817-818, March, **1996**.
4. Welker, H. *Physics Today*, Vol 29, pp.63-64, June, **1996**.

Schottky effect is increase in the discharge of electrons from the surface of a heated material by application of an electric field that reduces the value of the energy required for electron emission. The minimum energy required for an electron to escape the surface of a specific material, called the work function, is supplied by the heat. A very weak electric field may be applied that simply sweeps the already emitted electrons away from the surface of the material. When the field is increased, a point is reached for quite moderate fields at which the value of the work function itself is lowered. As the applied field (voltage) is further increased, the work function continues to decrease, so that the electron emission current continues to increase. At very high values of the applied field, however, the electron emission undergoes an excessive increase because of the onset of a different type of emission, called high-field emission or, simply, field emission. The effect is named after its discoverer, the German physicist Walter Schottky.

A Schottky barrier is created by the intimate contact of a metal and a semiconductor surface. The Figures below show the situation of a Schottky barrier of a metal and a p-type semiconductor.



A metal and a semiconductor before contact. Note the different Fermi levels which will cause electrons to flow to the semiconductor.



A Schottky barrier formed after contact of the metal and the semiconductor. A region of uncompensated charged acceptors results. This "space charge" causes a voltage drop at the interface.

At equilibrium, in the absence of externally applied voltages, the Fermi level must be constant throughout the sample, since otherwise a current would flow. In the metal the Fermi level is the top of the electron sea, while in the semiconductor, far from the interface, the Fermi level is determined ("pinned") by the impurity level. The Fermi level is matched in the following way: Before equilibrium, the Fermi level is lower in the semiconductor (when the work function of the polymer, $E_{vac}-E_F = \chi + V_n$, is larger than that of the metal, ϕ_m), therefore, electrons will flow from the metal to the polymer. This causes the build up of charges on both sides of the interface, resulting in an electric field and therefore a potential gradient according to Poisson's equation $d^2V/dx^2 = \rho(x)$. This is the so-called band bending. In this region, the electric field has caused the holes to move away from the interface; they drift to the top of the valence band. The result is that in this area -- of width *W* -- there is a surplus of negative charge caused by uncompensated charged acceptors, the "space charge region" or "depletion region", since there is an absence of majority carriers (holes in p-type semiconductors).

The parameters that describe the Schottky barrier are:

ϕ_{Bp} : barrier height. The barrier as seen by (majority) carriers coming from the metal. It depends on the difference in electron affinity of the metal and the semiconductor and (for p-type semiconductors) also depends on the energy gap $E_g = E_C - E_V$:

$$\phi_{Bp} = \chi + E_g - \phi_m$$

It is independent of the position of the Fermi level in the semiconductor and thus on the presence of impurities, etc. It might be lowered by the so-called image-force-lowering effect which adds to the energy scheme the potential caused by the interaction of the charge with its image (virtual) charge on the metal.

V_{bi} : built-in voltage or zero-bias band bending. The barrier as seen by (majority) carriers going into the metal. This is determined by the difference in Fermi level before contact:

$$V_{bi} = (E_{vac} - E_F)_{semicon} - (E_{vac} - E_F)_{metal} = \chi + V_n - \phi_m$$

W: depletion width. The width of the area devoid of (majority) carriers. The depletion width can be calculated when the doping profile is known (as will be shown in the next section).

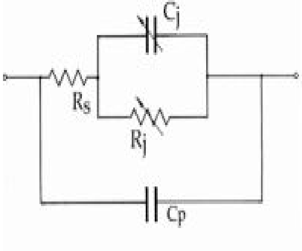
For a Schottky barrier the forward bias is when a positive voltage is applied to the (p-type) semiconductor and a negative voltage to the metal. This will compensate the band bending and diminish the barrier.

Similar to the Schottky barrier we have a pn-junction (of two equal semiconductors with different doping details) or a hetero-junction (of two different semiconductors). The theory of these devices is rather similar and will not be mentioned here further.

Schottky diode

Such a diode is one that has a metal-semiconductor contact (e.g., an aluminum layer in intimate contact with an n-type silicon substrate). It is named for the German physicist Walter H. Schottky, who in 1938 explained the rectifying behaviour of this kind of contact. The Schottky diode is electrically similar to a p-n junction, though the current flow in the diode is due primarily to majority carriers having an inherently fast response. It is used extensively for high-frequency, low-noise mixer and switching circuits. Metal-semiconductor contacts can also be nonrectifying; i.e., the contact has a negligible resistance regardless of the polarity of the applied voltage. Such a contact is called an ohmic contact. All semiconductor devices as well as integrated circuits need ohmic contacts to make connections to other devices in an electronic system.

Equivalent circuit of a Schottky Diode



The simplest lumped-equivalent circuit for the diode which is likely to give realistic estimates for its behaviour in a mixer or multiplier is illustrated in this Figure. In this diagram C_j is the parasitic capacitance of the space-charge region of the junction, R_j is the nonlinear resistance of the Schottky barrier, R_S is the series resistance of the epilayer, substrate and back contact and C_p is the parasitic capacitance of the package (if relevant). The parasitic inductance and fringing capacitance of the whisker are ignored.

Based upon this equivalent circuit the figure of merit normally used to evaluate the high-frequency performance potential of the Schottky-barrier diode is the cutoff frequency $F_c = 1 / (2\pi R_S C_o)$ where C_o is the zero-bias junction capacitance. The cut off frequency is thus seen to define the point at which the reactance of the shunting capacitance equals the series resistance. The series resistance R_S is frequency dependent and this can lead to a multivalued F_c in the submillimeter region, so one should not use F_c as the only figure of merit in selecting diodes for mm and submm application.