Schottky Diodes

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Introduction

Schottky diodes have been used for several decades as the key elements in frequency mixer and RF power detector circuits. In 1938 Walter Schottky, the son of German mathematician Friedrich Schottky, explained the manner in which a junction comprised of specific combinations of metals and a doped semiconductor material can rectify. The Schottky diode is the result of this work.

The Schottky Junction

The Schottky diode junction is formed by plating a very pure metal, typically by evaporation or sputtering while under vacuum, onto a wafer that has been doped with either p-type or n-type dopant atoms. As soon as these materials 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 across the metal and the semiconductor is called the contact potential, and is usually in the range 0.3 – 0.8 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. One important thing to note is that there is no flow of minority carriers from the metal into the semiconductor and thus no neutral plasma of holes and electrons is formed. Therefore, if the forward voltage is removed, current stops within a few picoseconds and reverse voltage can be established in this time. There is no delay effect due to charge storage as in junction diodes. This accounts for the predominant use of surface barrier diodes in microwave mixers, where the diode must switch conductance states at the rate of the frequency of a microwave local oscillator. The voltage-current relationship for a barrier diode is described by the law of the junction equation. The derivation is given in many text books (for example, Maas). Some examples of current vs. voltage curves for Schottky diodes of various barrier heights are shown in Figure 1.

Schottky diodes have been commercially available for several decades. Silicon Schottky diodes can be produced with several different barrier heights, as shown in the table below, but for practical reasons four main barrier heights are offered: high barrier, medium barrier, low barrier and “zero bias detector (ZBD)” barrier. The first three of these types are typically made with n-type Si and the appropriate metal; ZBD diodes generally are made with p-type semiconductor material. Gallium Arsenide (GaAs) Schottky diodes are fabricated with n-type doping only.

Junction Capacitance

The depletion region of the Schottky diode is an insulator that separates two conductive regions (the metal layer and the doped semiconductor layer), so it constitutes a parallel-plate capacitor. The capacitance of this region is determined by the physical dimensions of the junction as well as the doping profile of the semiconductor layer. The thickness of the depletion layer can be affected by the magnitude of an externally-applied voltage: a forward bias will reduce the thickness of the depletion layer, effectively moving the plates of the capacitor closer together; and, a reverse bias voltage increases the thickness of the depletion layer, effectively

Barrier height is a design variable for a Schottky diode, whereas it is fixed for a pn junction. This is another advantage of a Schottky junction relative to a pn junction: a Schottky junction can have significantly lower forward voltage at a given forward current than a comparable pn junction. A Schottky diode is a virtually ideal rectifier whose forward voltage can be selected by design. This makes Schottky diodes very well-suited for use as power detectors, especially at very low signal levels, and as the switching elements in commutating mixers.

The depletion capacitance is given by

\[
C_p = \frac{q}{eN_A}\ln\left(\frac{N_A}{n_0}\right)
\]

where

- \(q\) is the electronic charge
- \(e\) is the elementary charge
- \(N_A\) is the acceptor concentration
- \(n_0\) is the intrinsic carrier concentration
- \(qV\) is the depletion voltage

Junction Equation

The Schottky diode is the result of a practical application of junction theory.

The Shockley equation is an empirical equation that describes the voltage-current relationship for a Schottky diode. It is given by

\[
I = I_{SAT} e^{\left(-\frac{q\Phi_B}{nKT}\right)} - 1
\]

where

- \(I_{SAT}\) is the saturation current
- \(\Phi_B\) is the barrier height
- \(n\) is the ideality factor
- \(K\) is Boltzmann's constant
- \(T\) is the temperature

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- \(e\) is the elementary charge
- \(N_A\) is the acceptor concentration
- \(n_0\) is the intrinsic carrier concentration
- \(qV\) is the depletion voltage

The Shockley equation is used to describe the behavior of Schottky diodes and is a fundamental equation in semiconductor physics. It provides a way to calculate the current through a Schottky diode for a given voltage and barrier height. The equation is derived from the Poisson equation and the continuity equation in the depletion region of the diode.
spreading the parallel plates farther apart. The relationship between reverse bias voltage and diode capacitance is

\[ C_j(V_R) = \frac{C_j(0)}{1 - \frac{V_R}{V_t} \frac{kT}{q}} \]

where

- \( C_j(V_R) \) is the junction capacitance at reverse bias voltage \( V_R \)
- \( V_R \) is the reverse bias voltage from external voltage source
- \( C_j(0) \) is the junction capacitance with \( V_R = 0 \) V
- \( k \) is Boltzmann’s constant
- \( T \) is the absolute temperature
- \( q \) is the charge of an electron

Series Resistance
The series resistance of a Schottky diode is the sum of the resistance due to the epi layer and the resistance due to the substrate. The resistance of the epi is given by the following equation:

\[ R_{epi} = \frac{L}{q \mu_N N_d A} \]

where

- \( L \) is the thickness of epi in cm
- \( \mu_N \) is the mobility of electrons for n-type Si (for p-type silicon the mobility of holes would be used)
- \( N_d \) is the doping density of the epi layer in atoms/cm\(^3\)
- \( A \) is the area of Schottky contact in cm\(^2\)

The resistance of the substrate is given by the following equation:

\[ R_{sub} = 2 \rho_s (A/\pi)^{1/2} \]

where

- \( A \) is the area of Schottky contact in cm\(^2\)
- \( \rho_s \) is the substrate resistivity in \( \Omega \cdot \text{cm} \)

Mixer Diodes Compared To Detector Diodes

In radio receivers mixers are designed to convert radio frequency (RF) energy to an intermediate frequency (IF) as efficiently as possible. The reason for doing this is that very selective filters at the RF frequency are expensive, so the signal is converted to a lower frequency where good selectivity can be more easily achieved and where amplification can be accomplished with less expensive amplifiers.

The frequency conversion is obtained by operating a diode with fast response and high cutoff frequency as a switch, turning it on and off at a rate determined by the signal frequency of a local oscillator (LO). This commutating action produces signals at two new frequencies: the sum of the RF and LO frequencies and the difference of these two frequencies. The desired output frequency for downconverter applications is the difference frequency. A good mixer diode with a high cutoff frequency will be capable of low conversion loss (L_C). This, combined with a low noise figure in the IF amplifier, will result in a low overall receiver noise figure, unless the diode itself generates noise (other than normal thermal noise). Ideally, the mixer diode should accomplish this conversion with a minimum of LO power and no need for an external DC bias source.

Detector diodes are designed to rectify very low levels of RF power to produce a DC output voltage proportional to the RF input power. The diode may be operated at a small DC bias (typically 50 μA) which results in a relatively high RF impedance (typically 600 Ω). Very low diode capacitance is required to achieve high sensitivity. Since the detected output can be at a very low level, the low frequency (audio) excess noise (1/f noise) is an important consideration.

Schottky Diode Circuits

Mixer Circuits
There are many circuits utilized for frequency conversion. These circuits may comprise one or more Schottky diodes, and in some cases, transformers, to achieve frequency conversion. Local oscillator signal drives the diodes into and out of conduction at the rate of the LO frequency, while the RF signal is also present. Some examples of these circuits are shown below.

**Single-Ended Mixer**

A single-ended mixer consists of a Schottky diode and passive components utilized as filters. This configuration has the advantage that it contains few components. The disadvantages of this circuit are that isolation between the RF source, the LO source and the IF output depends on the performance of the filters.

**Singly-Balanced Mixer**

A singly-balanced mixer is typically composed of a pair of Schottky diodes driven by a 180° hybrid coupler. The IF output is obtained through a low pass filter. This circuit offers better interport isolation and noise performance than a single-ended mixer, at the minor cost of a couple more components. Schottky diodes connected as shown in the circuit below are available in single packages and as monolithic chips. This diode configuration is known as a series tee.
Doubly-Balanced Mixer
The doubly-balanced mixer is comprised of four Schottky diodes, connected anode-to-cathode in a ring, and a pair of transformers. This configuration offers very good interport isolation and low conversion loss. Monolithic Schottky diode ring quads are available in several package styles and as chips.

This mixer configuration offers very good interport isolation and conversion loss.  

Subharmonic Mixer
The subharmonic mixer utilizes the nonlinear impedance of an antiparallel pair of Schottky diodes in two different ways: it uses the diodes as a commutating switch and also as a harmonic generator. Harmonics of the local oscillator signal are generated by the diodes. These harmonics are mixed with the RF signal as well. This arrangement allows a local oscillator of lower frequency to produce an IF signal with a very high frequency RF signal – thus allowing low signal, low frequency local oscillator circuits to be utilized to down convert millimeter wave signals. The subharmonic mixer is a single-ended mixer, so its interport isolation also depends upon the performance of the filters in the circuit.

Mixer Diode Barrier Height
The barrier height of the Schottky mixer diode determines the amount of LO power required, as well as the mixer’s nonideal performance characteristics such as intermodulation distortion. Generally speaking, the higher the diode barrier height, the greater the required LO signal amplitude and the lower the intermodulation distortion products will be. Also, the greater the number of Schottky diodes in the mixer circuit, the greater the LO power must be for proper operation. Mixer diodes are available with low, medium and high barriers. Examples of series tee diodes of various barrier heights available from Skyworks are listed in the Table 1.

Detector Circuits
Schottky diode detector circuits are basically simple rectifier circuits which produce a low frequency (nominally DC) output current or voltage which is proportional in magnitude to the magnitude of the RF input signal. Detector circuits are often used to monitor the output level of a power amplifier in a radio transmitter, or they can simply indicate the presence or absence of an RF signal.

In this example, the Schottky response transitions from square law to linear detection when the input signal level is approximately -20 dBm. The level at which this transition occurs is proportional to the barrier height of the diode. The curve shown here is for a so-called “zero bias diode (ZBD)” detector diode, which has the lowest available barrier height for Si Schottky diodes. This diode is the most sensitive detector, due to its very low forward voltage.

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The appellation “ZBD” can cause confusion; any Schottky diode can be used as a detector without requiring an external bias source. However, the higher the barrier height the less sensitive the diode is to very small signals. If the diode

<table>
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<tr>
<th>Freq.</th>
<th>Cj OV, 1 MHz (pF)</th>
<th>Rs 5 mA (Ω)</th>
<th>Vb 10 uA (V)</th>
<th>Vf 1 mA (mV)</th>
<th>Drive Level</th>
<th>Beam Lead</th>
<th>Epoxy Package</th>
<th>Hermetic Package</th>
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<td>Min</td>
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</table>

Figure 6: Single Schottky Diode Detector
is slightly forward biased with an external current source, sensitivity to small signals can be improved. The ZBD was developed to eliminate the need to use an external bias source in a very sensitive detector, thus the nomenclature “ZBD.”

**Diode Configurations and Packaging**

Modern RF and microwave systems often must be manufactured at low cost without compromising performance. Schottky diodes in surface mount packages have proliferated as a result. Many of these packages, such as those from the JEDEC SOD and SOT families, offer a reasonably good combination of low cost and RF performance, in some cases for signal frequency as high as 10 GHz. Examples of such diodes are the SMS1546, SMS7621 and SMS7630 family of detector diodes, which are available in the SOT-23, SOT-143, SOD-323, SC-70 and SC-79 packages, as well as a very small land grid array package. Examples of mixer diodes in surface mount plastic packages include SMS3922, SMS3923 and SMS3924 families, also available in the packages listed above, as well as in the SC-88 package.

These packages facilitate the assembly of the diode to a printed circuit board, afford some protection to the die from ambient conditions such as humidity, and also facilitate the assembly of diode arrays, such as series pairs, for use in circuits that require more than one diode for proper operation. These advantages do not come without a cost; the internal bond wires that are utilized to make connections, as well as the lead frames or other internal metal conductors, present parasitic inductance that is in series with the diode junctions. In addition to this parasitic inductance, there is also parasitic package capacitance that typically is in parallel with the diode junctions. These parasitic reactances cause the RF performance to increasingly deviate from the ideal performance as signal frequency increases.

The equivalent circuit for a single junction diode in a package is shown in Figure 9. Clearly, the series inductance will reduce the amount of input signal voltage across the diode junction. The parallel package capacitance shunts some of the signal current around the diode junction. These two reactances also interact with each other to produce a parallel resonant circuit which also will behave in a manner that deviates substantially from that of the die by itself.

For high frequency applications in which package parasitic reactances are particularly troublesome, two other die configurations have been developed which allow the die to be connected to an external circuit without the need for a diode package. These configurations are known as beam lead diodes and flip chip diodes.

Beam lead diodes consist of a Schottky junction which is formed on the top surface of a wafer, as would be the case for a conventional vertical die structure. However, in a beam lead structure there are metalized areas deposited on the top of the wafer at each diode position. One of these metalized structures makes contact with the anode contact of the junction. The other metal structure, which is in line with the anode terminal, connects through a metal via to the cathode layer of the diode. After these metalizations are formed, the semiconductor material in the wafer that is between the diodes is etched away, thereby separating the individual beam lead diodes from each other. The product of this process is a bit of semiconductor material that contains the Schottky diode, with two metalized strips that connect to the anode and cathode of the diode and extend beyond the edges of the die. These metal beams are used to connect the diode to the circuit assembly and to suspend the diode.

The beam lead structure substantially eliminates the parallel parasitic capacitance and almost completely eliminates the series inductance of a comparable packaged device. However, these advantages come at the cost of more difficult handling of the diode and the more difficult circuit attachment techniques -- in addition to the loss of the protection afforded by a package encapsulant. The substantial improvement in high frequency performance, however, these disadvantages, especially at frequencies from approximately 10 GHz and higher.

Another, even more significant advantage of the beam lead structure is the ability to reduce the contact area of the active junction to reduce its capacitance. Since the electrical contact of the junction’s anode is made with evaporated or sputtered metal rather than by a bond wire, the junction area can be made arbitrarily small. In a vertical die which is placed in a package, the top contact area not only defines some of the electrical characteristics of the diode, it also must be sufficiently large (typically 0.003 inches diameter minimum) to allow reliable connection of
a bond wire. This minimum top contact diameter effectively imposes a minimum die capacitance which can be produced in a vertical structure die. The beam lead structure eliminates this restriction.

A flip chip diode has almost all of the advantages of a beam lead diode without the handling and circuit-attach difficulties of the beam lead. Skyworks has recently introduced two flip chip Si Schottky detector diodes, SMS7621-096 and SMS7630-093, which fit in the industry-standard 0201 component footprint. These devices are fabricated much the same as a beam lead diode, with the exception that the strips of metallization from the anode and cathode of the junction connect to square metal terminals on the same face of the diode in which the junction resides. These pads are electrically isolated from the diode’s substrate. Attachment to the circuit is accomplished by flipping the diode junction-side-down and either soldering or connecting with conductive epoxy to the external circuit. The very low package parasitic reactances and excellent electrical performance of the beam lead diode are available in this diode configuration without some of the handling and attachment challenges presented by beam lead diodes.

Gallium arsenide (GaAs) Schottky flip chip diodes are also available.

The significantly higher electron mobility of GaAs allows GaAs Schottky diodes to perform well in the millimeter wave bands. Skyworks’ DMK2790-000 and DMK2308-000 are two such devices. The DMK2790-000 is a single Schottky diode in the flip chip configuration, while DMK2308-000 is an antiparallel pair which typically is used in subharmonic mixer circuits.

Conclusion

The Schottky junction is widely utilized in frequency mixing and RF power detection circuits, due to the nearly ideal performance of Schottky diodes.

References
