Zero Bias Detector Diodes for the RF/ID Market

Hewlett-Packard's newest silicon detector diodes were developed to meet the requirements for receiver service in radio frequency identification tags. These requirements include portability, small size, long life, and low cost.

by Rolando R. Buted

Tracking of products and services is critical in today's highly competitive and rapidly growing world of manufacturing and service industries. To succeed in these industries, accurate and timely information is required.

Two widely used tracking methods are bar code readers and magnetic stripe. Although commonplace, they are both limited in their range and their operating environment. For example, bar codes require a direct line of sight within a few inches and a relatively clean and benign environment to operate reliably.

In contrast, a radio frequency identification (RF/ID) system uses radio signals to communicate. Line of sight is not needed and the system can operate in hostile environments characterized by water, oil, paint, and dirt. It can even be used for communication through cement, glass, wood, or other nonmetallic materials. These wireless systems are being successfully used to identify and track cattle, household pets, cars passing through toll booths, supermarket carts, railroad cars, and personnel entering and leaving secure facilities.

An RF/ID system is composed of two components: a reader (interrogator), which contains both transmitter/receiver and decoder/control modules, and a tag (transponder), which typically contains an antenna and a receiver circuit. Since a system normally has only a few interrogators but many tags, the most severe design constraints are on the tag. These constraints include portability, small size, long life, and low cost. Hewlett-Packard's newest silicon detector diodes (HSMS-285x) were developed to address these constraints.

RF/ID Technology

RF/ID tags can be active or passive. Active tags have an onboard power source (a battery) so that less power is needed from the reader, and usually have a longer read range. However, they have a limited life span and are generally more expensive to manufacture.

Passive tags do not need a separate external power source. They derive their operating power from the energy sent by the interrogator. Passive tags are lighter and cheaper than active tags and have virtually unlimited lifetime. Some passive tags contain a battery to maintain internal memory information in read/write applications. The trade-off is that passive tags have a shorter read range than active tags and require a much higher-powered reader to supply the energy needed to operate them.

RF/ID tags can be read-only or read/write. Read-only tags, as the name implies, can only be read, but can be read millions of times. Read/write tags allow the data stored in them to be altered in addition to being read.

Whether the tag is passive or active, read-only or read/write, it requires a receiver circuit. Receiver circuits can be of two types: superheterodyne or crystal video (Fig. 1). Because the superheterodyne receiver contains RF and low noise amplifiers, its detection sensitivity is typically −150 dBm. The crystal video receiver, on the other hand, is limited to only about −55 dBm. However, it is simpler and much cheaper than the superheterodyne receiver, so the RF/ID industry has adopted it for use in tags. The superheterodyne receiver is used in interrogators.

The crystal video receiver of Fig. 1 can take different forms, depending on the application. Four common configurations are shown in Fig. 2. The single-diode circuits offer simplicity and low cost, whereas the voltage doubler circuits provide a higher output for a given input. Each type can be designed with conventional n-type Schottky diodes or zero biased p-type Schottky diodes. If n-type diodes are used, an external dc bias source is needed for detection operation at low input power levels (<1 mW) because of the low saturation current. The p-type zero bias diode does not need a bias source because it has a relatively high saturation current. In addition, it offers the lowest possible cost, size, and complexity, and

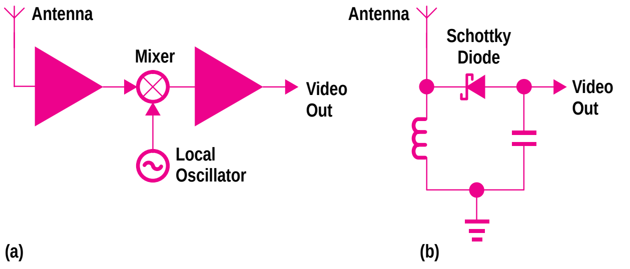

Fig. 1. (a) Superheterodyne receiver. In RF/ID applications, this receiver type is used mainly in interrogators. (b) Crystal video receiver. This type is used in RF/ID tags.

Backscatter RF/ID Systems

Automatic vehicle identification (AVI) is one aspect of intelligent vehicle-highway systems (IVHS). It is a good example of the use of RF/ID technology in a practical application. For example, RFID systems are being integrated into electronic toll collection at bridges so that tolls can be deducted from an account by using information stored in a tag mounted in the vehicle's windshield.

One of the key requirements of these systems is that the stationary reader (interrogator) be able to discriminate between individual tags passing the toll booth without interference from other tags or other transmitters that may be operating at the same frequency. Backscatter modulation technology is one method that can be used for such an application.

A block diagram of a typical transponder (tag) for backscatter technology is shown in Fig. 1. The interrogator (reader) sends a modulated RF signal that is received by the tag. The Schottky diode detector demodulates the signal and transfers the data to the digital circuits of the tag. The radar cross section of the tag is changed by a frequency shift keying encoder and switch driver so that the reflected (backscattered) signal from the tag is modulated and ultimately detected by the reader's receiver antenna. Thus, communication between the tag and reader is established.

By using backscatter technology, interference from nearby transmitters can be avoided, since the reader controls the frequency of operation and can shift it if nearby transmitters are operating at the same frequency. Also, the reflected signal strength from the tag is proportional to the incident interrogator signal, so tags outside the incident beam focus area will reflect a weaker signal that the reader antenna can reject.

Such a backscatter tag can have read/write capabilities that allow flexible digital formats. It can also contain various tag information that can be used in other IVHS applications. A specific minimum field strength is required to put the Schottky detector diode into forward bias so that the tag does not backscatter until the interrogator signal and message data are received, thus minimizing the power requirements of the tag.

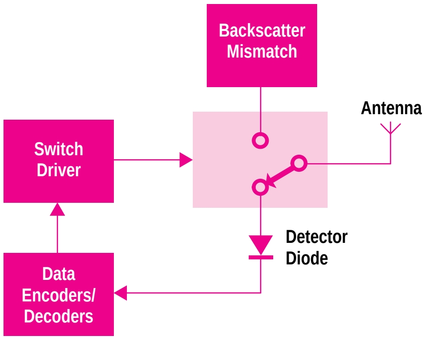

Fig. 1. Typical transponder block diagram for backscatter RF/ID technology.

usually exhibits the lowest flicker noise. It is therefore the diode of choice for RF tag applications.

The performance of an RF/ID system is directly related to the frequency range in which it is used. The higher the frequency, the faster the data transfer rate and the longer the read/write range. The tag's *capture window* is more focused at higher frequency. Metals absorb low-frequency signals more than high-frequency signals, whereas obscuring materials such as dirt and grease absorb high-frequency signals more than low frequency signals. Most RF/ID systems operate in three basic frequency ranges. The high-frequency ranges include 850 to 950 MHz and 2.4 to 2.5 GHz. The low frequency range is 100 to 500 kHz, close to the range of AM radio stations. Some applications, such as auto toll collection, also use 5.86 GHz and 10.5 GHz.

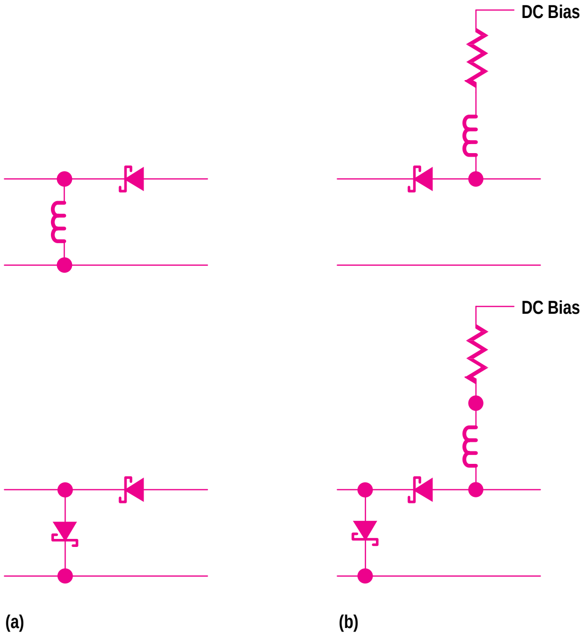

Fig. 2. Different crystal video receiver configurations. (a) Zero bias Schottky diodes. (b) Conventional n-type Schottky diodes.

Device Theory

A Schottky diode is simply a metal layer deposited on a semiconductor such as silicon. To improve its performance and reliability, it can be passivated with silicon dioxide or silicon nitride or both.

The equivalent circuit of a Schottky diode is shown in Fig. 3, along with package parasitic elements. In the diode chip, R_S represents the series resistance of the diode, which includes bulk and contact resistances. Junction capacitance C_j is determined to a first-order approximation by the metal used, the silicon doping, and the active area. R_j is the junction resistance, often called the video resistance R_V, and is a

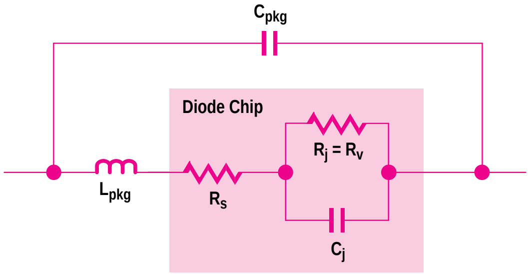

Fig. 3. This model describes an SOT-23 packaged Schottky diode to 10 GHz with good accuracy.

function of the total current flowing through the device. Low C_j, R_v, and R_s are desired for an efficient detector diode.

The total current I flowing through a Schottky diode is given by:

$$I = I_s\left[\exp\left(V_b/nV_t\right) - 1\right] ,$$

where I_s is the diode saturation current, V_b is the voltage across the Schottky barrier, n is the ideality factor, and V_t is the thermal voltage. The voltage across the Schottky barrier is equal to an applied voltage V_a minus any voltage drop across the series resistance R_s, that is, $V_b = V_a - IR_s$. At low bias levels, R_s can be neglected, so $V_b \approx V_a$.

The video resistance is $R_v = dV_b/dI$, so for small I_s:

$$R_v = nV_t/I .$$

For the zero bias condition, $V_a = 0$, at room temperature with n = 1, the video resistance simplifies to:

$$R_v = 0.026/I_s .$$

By increasing I_s, the video resistance of the diode at zero bias is minimized. I_s is increased by proper selection of the metal type and the semiconductor doping. For silicon, p-type generally gives a higher I_s than n-type. However, p-type silicon has higher R_s than n-type silicon with the same doping. Increasing the silicon doping to lower the R_s also increases C_j, which degrades the detector performance. N-type Schottky diodes are seen in mixer applications because of the lower R_s and the fact that R_v can be kept low by using high local oscillator drive levels.

Design Goals

An important performance characteristic used to describe video detector diodes is voltage sensitivity, or γ. This parameter specifies the slope of the curve of output video voltage versus input signal power, that is:

$$V_o = \gamma P_{in} .$$

Neglecting parasitic and reflection losses, voltage sensitivity can be defined as:

$$\gamma = \beta/(\partial I/\partial V) ,$$

where β is the current sensitivity and has a theoretical value[1] of 20 A/W. Using the diode equation (with ideality factor n = 1):

$$\partial I/\partial V = I/0.026 .$$

Therefore,

$$\gamma = 0.52/I .$$

For zero bias detectors, $\gamma = 0.52/I_s$.

This simple analysis of a perfect detector gives a poor approximation to the actual data on existing diodes. To bring the analysis closer to reality, effects of diode junction capacitance, diode series resistance, load resistance, and reflection loss must be considered.

Diode Capacitance and Resistance. In most cases, the junction impedance associated with R_v and C_j is much greater than R_s, especially at low frequencies. However, at high frequencies, the junction impedance is reduced so that the RF power dissipated in R_s is comparable to that of the junction. Incorporating the effects of the diode capacitance and resistance on the current sensitivity,[2] the voltage sensitivity for the zero bias diode becomes:

$$\gamma_1 = 0.52/\left(I_s\left(1 + \omega^2 C_j^2 R_s R_v\right)\right) .$$

where $\omega = 2\pi f$, C_j is junction capacitance, I_s is diode saturation current, R_s is the series resistance, and R_v is the junction resistance.

Load Resistance. The diode resistance R_v at zero bias is usually not small compared to the load resistance R_L. If the diode is considered as a voltage source with impedance R_v feeding the load resistance R_L, the voltage sensitivity will be reduced by the factor $R_L/(R_L + R_v)$, or:

$$\gamma_2 = \gamma_1\left(R_L/\left(R_v + R_L\right)\right) .$$

For example, a typical load resistance is 100 kΩ. If R_v is 5 kΩ, then

$$\gamma_2 = \gamma_1(0.952) .$$

Reflection Loss. Further reduction in voltage sensitivity is caused by reflection losses in the matching circuit in which the diode is used. In Fig. 3, the package capacitance C_{pkg} and package inductance L_{pkg} can be used to determine the packaged diode reflection coefficient. If this diode terminates a 50Ω system, the reflection coefficient ρ is:

$$\rho = \left(Z_D - 50\right)/\left(Z_D + 50\right) ,$$

where Z_D is a function of frequency and the package parasitics. If there is no matching network, the voltage sensitivity can be calculated as:

$$\gamma_3 = \gamma_2\left(1 - \rho^2\right) .$$

The chip, package, and circuit parameters all combine to define an optimum voltage sensitivity for a given application. Our design goal was to develop a diode to operate in the frequency range used in RF/ID tags. Using the voltage sensitivity analysis described above, we hoped to produce an optimum, low-cost, manufacturable part in the shortest time possible.

Implementation and Fabrication

Hewlett-Packard's preeminent zero bias detector diode (HSCH-3486) already provides excellent detection sensitivity in an axially leaded glass package, particularly at high frequencies. To meet our design goals, the project team decided to leverage the HSCH-3486 technology.

We chose the plastic SOT-23 package because of its low manufacturing costs for high-volume products. Using the SOT-23 package, several modifications were possible that we hoped we could take advantage of. Before building prototype devices, we made a detailed device model for the HSCH-3486. The model helped us fabricate an optimum device with minimum design iterations.

Two-dimensional process and device simulators were used to model and predict the performance of the HSCH-3486. Diode parameters such as silicon doping, area, epitaxial layer thickness, metal pad size, and passivation thickness were included to study the effects that these process parameters had on diode electrical performance and ultimately on detector performance. A typical sensitivity analysis (Fig. 4) showed the effect of contact area and epitaxial thickness on voltage sensitivity γ_3, assuming an ideal matching circuit. The model was also used to check for sensitivity to parameters that are not directly measurable during processing, such as surface states and recombination velocities. The model was good for trend analysis but could not be used to predict absolute values until devices were fabricated and tested.

Using the various equations for voltage sensitivity, it is common to plot γ_2 as a function of the saturation current I_S, as shown in Fig. 5, for given values of C_j, R_S, and R_L. Since C_j, R_S, R_V, and I_S interact with one another, it is not simple to lower C_j, say, without increasing R_S. By using the model, we were able to select the best combination of these parameters to maximize the voltage sensitivity at a given frequency. The process model ensured that our design was within the limits of our existing manufacturing capability. In this way, we were able to minimize development costs and time to market.

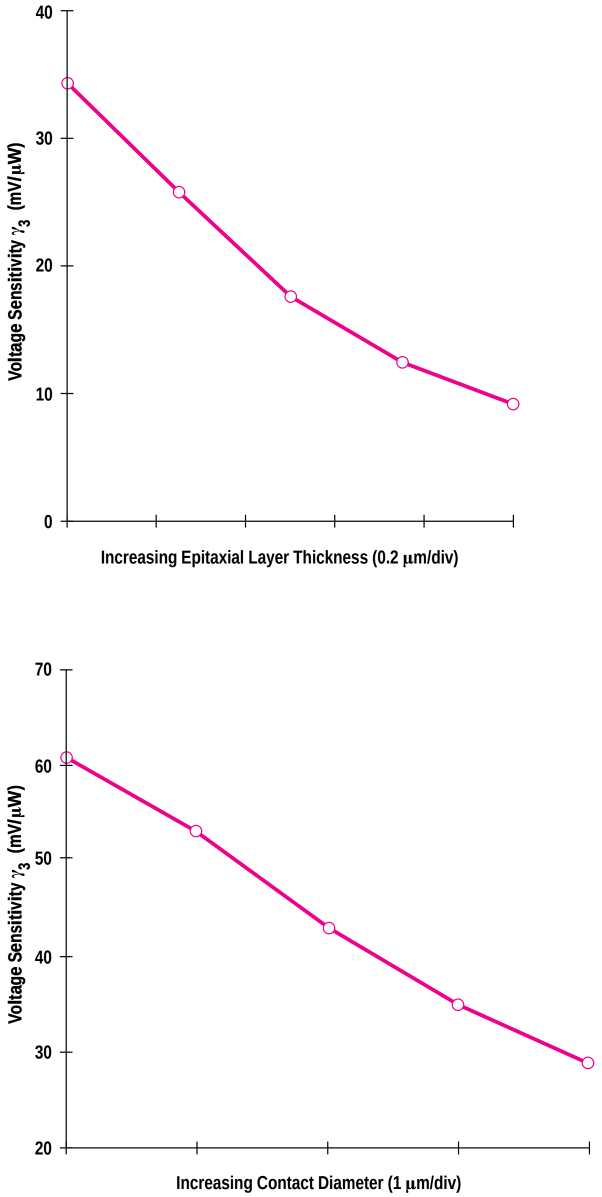

Fig. 4. Effects of epitaxial layer thickness and contact area on voltage sensitivity. f = 5.8 GHz. R_L = 100 kΩ.

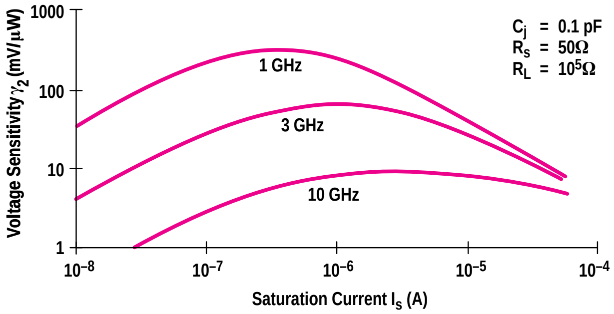

Fig. 5. Voltage sensitivity as a function of saturation current.

The fabrication process is relatively simple. Using a heavily doped silicon wafer substrate (to keep R_S low), an epitaxial layer is grown with tight controls on the doping level, thickness, and doping transition width. After silicon dioxide and nitride passivation, photolithography is used to define a contact window. A well-controlled metal process is used to deposit the metal, which defines many of the critical parameters. The metal is etched to an appropriate size for bonding in the plastic package. The wafer is cut into individual die and attached to a leadframe using a silver epoxy. It is then molded into the final plastic configuration. Fig. 6 shows the device cross section and die layout.

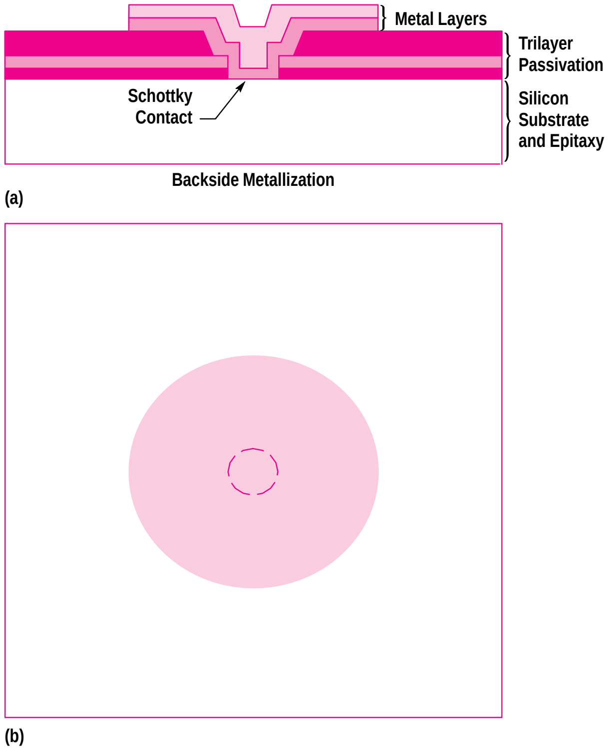

Fig. 6. (a) HSMS-2850 diode cross section. (b) Die layout.

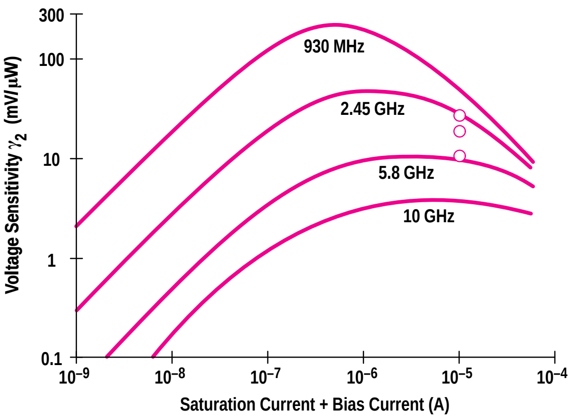

Fig. 7. Calculated voltage sensitivity for zero bias Schottky diodes having R_s = 55Ω and C_j = 0.15 pF. R_L = 100 kΩ. Dots show measured values for 930 MHz, 2.45 GHz, and 5.8 GHz.

The packaged device can be 100% tested for various dc parameters such as forward voltage bias V_f and breakdown voltage V_{br}. Many of the dc parameters have been correlated with high-frequency parameters, thus ensuring the performance of each part and eliminating the high costs associated with high-frequency tests.

Performance

The initial lots that were processed after being designed in the process and device simulator performed very closely to the predicted values. Minimal model changes were necessary. In fact, the results were sufficiently good that no design iterations were necessary and the data sheet specifications were set using those lots. Although we did not experience the normal kinds of process variation that we would expect over a long period of time, our confidence in the model accuracy allowed us to simulate these variations to show that the specification would still be met. In addition, we could use the model to determine what process and device parameters could be changed for future improvements to the diode.

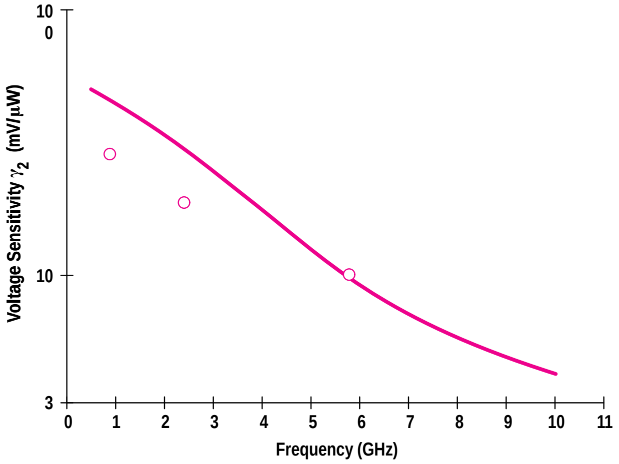

Fig. 8. Calculated voltage sensitivity of the HSMS-2850 zero bias Schottky detector diode. Dots show measured values.

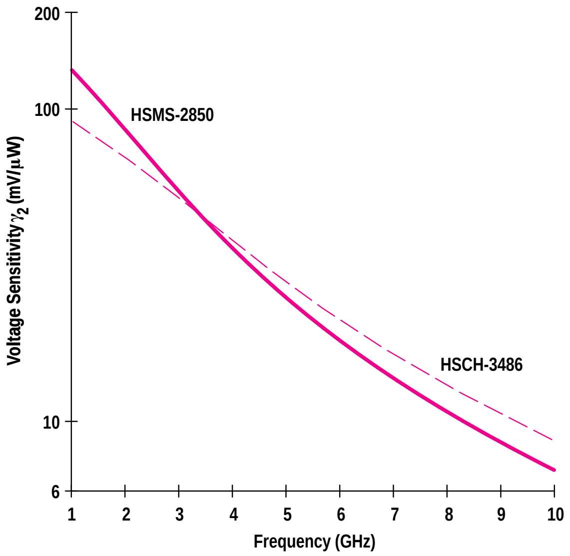

Fig. 9. Comparison of two zero bias Schottky diodes.

Figs. 7 and 8 show actual voltage sensitivity compared to the calculated values.

For comparison with the HSCH-3486 glass package diode, Fig. 9 shows γ_2 as a function of frequency. The different values of C_j, R_s, and I_s of the two diodes cause the HSMS-2850 to provide greater performance at frequencies less than 3 GHz while the HSCH-3486 is superior above 3 GHz. Because of its simpler packaging and testing, the HSMS-2850 is much lower in cost than the HSCH-3486.

Conclusion

Hewlett-Packard's newest silicon zero bias detector diode has one of the best price/performance ratios on the market. We feel that these diodes will become an integral part of many tag applications being designed today and will be considered in future designs and technology. They provide excellent voltage sensitivity for many of the frequency ranges being used in the RF/ID industry at a very low cost.

Acknowledgments

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2. H.C. Torrey and C.A. Whitmer, *Crystal Rectifiers*, MIT Radiation Laboratory Series, Vol. 15, McGraw-Hill, 1948.