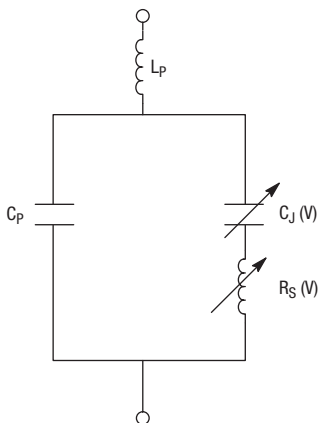


APPLICATION NOTE

# Varactor Diodes

## Introduction

A varactor diode is a P-N junction diode that changes its capacitance and the series resistance as the bias applied to the diode is varied. The property of capacitance change is utilized to achieve a change in the frequency and/or the phase of an electrical circuit. A simple model of a packaged varactor diode is shown below:



In the above figure,  $C_J(V)$  is the variable junction capacitance of the diode die and  $R_S(V)$  is the variable series resistance of the diode die.  $C_P$  is the fixed parasitic capacitance arising from the installation of the die in a package. Contributors to the parasitic capacitance are the package material, geometry and the bonding wires or ribbons. These factors also contribute to the parasitic inductance  $L_P$ . The contribution to the series resistance from the packaging is very small and may be ignored. Similarly, the inductance associated with the die itself is very small and may be ignored.

Variation of the junction capacitance and the junction series resistance as a function of applied reverse voltage is reported in the individual varactor data sheets of this catalog.

A common package configuration is to assemble two junctions in one package in a common cathode or common anode configuration. An empirical model for this dual configuration assumes the same value of parasitic capacitance in parallel with each junction die as for a single junction assembly. On the other hand, the parasitic inductance  $L_P$  may be assumed to be common for the assembly. For example, suppose two junctions

each with a junction capacitance of 0.5 pF ( $C_J = 0.5$  pF) are assembled together in one package which has a parasitic capacitance of 0.15 pF ( $C_P = 0.15$  pF) and a parasitic inductance of 0.5 nH ( $L_P = 0.5$  nH). The model for this case may be represented by two diodes with total capacitance of 0.65 pF each ( $C_J + C_P = 0.5 + 0.15$ ) in parallel or in series depending on the configuration. The inductance of 0.5 nH would appear in series with the entire assembly.

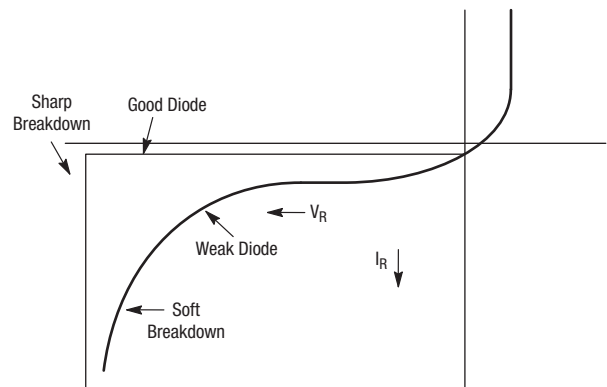
## Key Electrical Parameters

The key electrical parameters guiding the selection and usage of a varactor diode are

- Reverse breakdown voltage and reverse leakage current.
- Capacitance value and the capacitance-voltage change behavior.
- Quality factor (also known as figure of merit),  $Q$ .

## Reverse Breakdown Voltage and Reverse Leakage Current

The reverse breakdown voltage ( $V_B$ ) and the reverse leakage current ( $I_R$ ) are typically measures of the intrinsic quality of the semiconductor diode. Their effect on the frequency or phase tuning behavior is only indirect and of secondary importance. The IV characteristics of a good-quality diode and a weak diode are depicted in the following figure.



The reverse breakdown voltage is normally measured at 10  $\mu$ A of reverse leakage current. In a well-constructed diode, the breakdown occurs when the electric field across the diode reaches the limit that causes an avalanche of conductors through the diode. The breakdown voltage, therefore, defines the operating limit for the reverse bias across the diode. A rule of thumb is to specify the reverse breakdown voltage a minimum of 5 V above the maximum operating reverse DC voltage.

The breakdown voltage of the diode is determined by the density of dopants in the semiconductor. Higher dopant density translates into a lower breakdown voltage. An equally important factor determining the breakdown is the defect density (mostly an outcome of wafer fabrication processes). Hence, when a diode breakdown voltage is low, it could be either intentional in an effort to lower the resistance and increase the diode Q, or unintentional—simply an outcome of poor wafer processing. Because of this latter factor, a low breakdown voltage is not necessarily an indicator of a high diode Q. Therefore, it is not a good idea to specify an upper limit on breakdown voltage as a means of specifying high diode Q. It is better to specify directly a minimum acceptable limit on diode Q.

The reverse leakage current drawn by the diode is a direct measure of the diode quality as opposed to the reverse breakdown voltage. In a well-constructed varactor diode, depending on the geometry and the junction size, the leakage current can be less than a nanoampere to a couple of hundreds of nanoamperes. A larger leakage current is usually the result of excessive defects in the semiconductor that present shortcut passage for movement of electrons and holes.

As shown in Figure 1, a good quality diode draws a very small leakage current up to the avalanche breakdown point. A soft diode, on the other hand, draws a greater and greater leakage current as the bias applied to the diode is increased. The reverse leakage current is typically specified at 80 percent of the rated breakdown voltage.

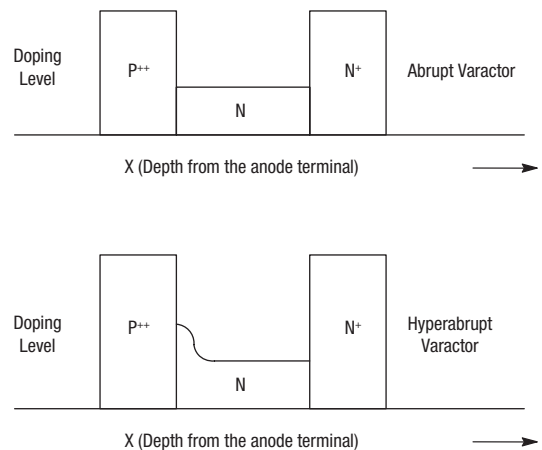
The reverse leakage current is also the best indicator of the diode stability through a stress cycle such as burn-in. Of all the measurable parameters, a shift in leakage current at a given bias voltage is the most sensitive measure of the diode’s ability to withstand the burn-in stress.

The reverse leakage current of a varactor diode increases rapidly with temperature as the motion of carriers is enhanced by the thermal energy. A rule of thumb is that a fiftyfold increase in leakage current is obtained by an increase in temperature from 25 °C to 125 °C, or double the current for every 10 °C.

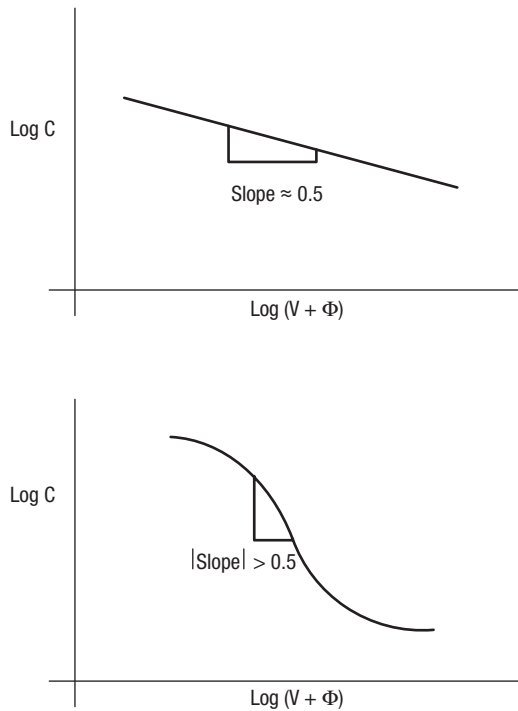
### Capacitance

The absolute capacitance of the varactor diode contributes to the total capacitance of the LC circuit in which it operates, and thus determines the frequency of operation. Additionally, the change of capacitance of a varactor diode with the change of applied reverse bias voltage is what governs the change of the frequency or the phase of the signal. Therefore, both parameters—the absolute capacitance value as well as the capacitance variation property—are extremely important for a user to understand.

The capacitance and the capacitance change characteristic are both functions of the doping structure introduced within the semiconductor during the wafer fabrication process. For example, note the difference in the doping characteristic of an abrupt and a typical hyperabrupt diode.



The difference translates into the following capacitance-voltage variation characteristic.



The slope of the log C vs. log V curve is typically denoted by gamma ( $\gamma$ ). For an ideal abrupt varactor diode, gamma is 0.5. However, a gamma of 0.47 is more representative of a practical abrupt varactor diode.

$$C = \frac{C_0}{(V/\Phi + 1)^{0.47}}$$

The value of built-in potential  $\Phi$  is 0.7 V for silicon and 1.3 V for gallium arsenide.

The modeling of the capacitance change of a hyperabrupt varactor is more complex. The slope of the log C vs. log ( $v + \Phi$ ) curve typically varies with the applied reverse bias. Hence, a description of capacitance change with voltage in terms of gamma is an approximation at best. If the range of applied bias used is sufficiently narrow, then one may use an equation with an average value of gamma over that range. If the range of applied bias used is wide, then the common practice is to use a curve-fitting technique to generate a model. The user may refer to capacitance-voltage curves presented for each part type. These curves are based on actual data from a typical diode in each group. Please contact the factory should you need more detailed data on capacitance-voltage change for a specific diode type.

The capacitance of a varactor diode changes with temperature. Capacitance increases as the temperature increases and decreases as the temperature drops. The following empirical relationship may be used to predict the temperature coefficient of capacitance (ppm change in capacitance per degree C change in temperature).

$$\begin{aligned} T_{CC}(V) &= \frac{1}{C(V)} \cdot \frac{dC(V)}{dT} \times 10^6 \\ &= \frac{K \cdot \gamma(V)}{(V + \Phi)} \end{aligned}$$

The value of parameter K may be assumed to be 2,300 for an abrupt varactor and 1,700 for a hyperabrupt varactor.

It follows from the above equation that the higher the gamma, the higher the  $T_{CC}$ ; i.e., the higher the sensitivity of capacitance to voltage, the higher the sensitivity of capacitance to temperature. The capacitance of hyperabrupt diode is more sensitive to temperature in comparison to the abrupt diode. Additionally, hyperabrupt diodes with higher gamma (i.e., higher capacitance ratio) are more sensitive to temperature than the ones with relatively smaller gamma.

Capacitance values reported in this catalog are measured at 1 MHz. Numerous experiments have shown that the junction capacitance is constant with frequency. A 1 MHz capacitance bridge or meter must operate with a low signal voltage to avoid errors due to the nonlinear properties of the varactor. Typically, about 15 millivolts RMS is recommended. A balanced measuring circuit must be used so that stray capacitance to ground of the measurement setup will be negligible.

In any real, physical environment the electric fields across any capacitor fringe away from the active or dielectric material into the surrounding space and are terminated on nearby or remote conductors. This contributes to the fringe capacitance and is inherent to any capacitor. Some of this fringing is properly associated with the dielectric chip, as Figure 1 indicates. Clearly, the fringing fields shown here, because they exist (and cannot be reduced in any practical way) for all environments, are properly considered as part of the junction capacitance.

Let's now take the chip and mount it in one of the many metal-ceramic packages available.

We have added the following items:

1. A metal pedestal upon which the chip rests.
2. Bonding wires, or straps, to contact the top of the chip.
3. A ceramic envelope (almost always Alumina,  $\sigma = 10$ ).
4. Various pieces of metal, copper or Kovar, to hermetically seal the package and provide mounting prongs.

We have also added capacitance:

1.  $C_S$ , from the straps to the pedestal and the base.
2.  $C_C$ , the ceramic capacitance.
3. More fringing  $C_F$  from the top of the package to the bottom and to the surrounding environment.

The strap and ceramic contributions are inherent to the package and are generally lumped together as  $C_P$ . The fringe capacitance, because it is dependent upon the exact method of mounting the package and the mechanical (conductive or dielectric) environment, is not inherent to the package and accordingly cannot be included in the diode specification. This capacitance is subject to control by the user, not the manufacturer.

Therefore, when the capacitance of the packaged tuning varactors is measured, a so-called fringe-free holder is used.

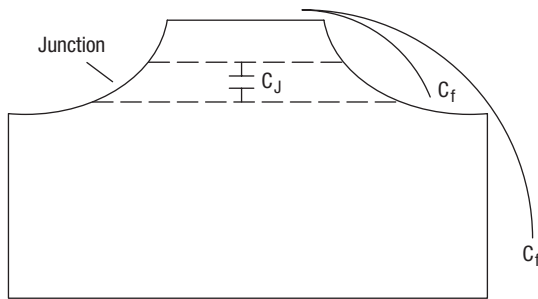


Figure 1. Inherent Chip Fringe Capacitance

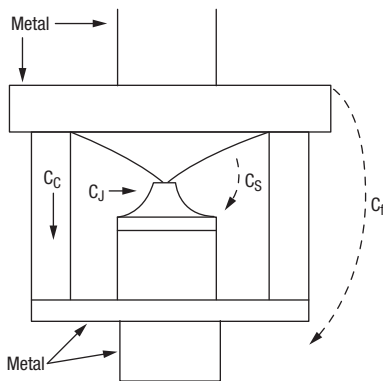


Figure 2. Stray Capacitance for Packaged Diodes

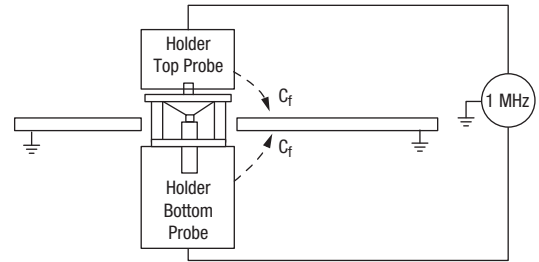


Figure 3. Fringe-Free Capacitance

We belabor this point because it is quite often a serious point of contention between customer and manufacturer, especially for low  $C_J$  varactors where theoretical capacitance ratios are often hard to obtain.

### Quality Factor (Q)

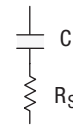
The Q factor, also known as the figure of merit and the quality factor, is an important parameter for a varactor diode since it determines the frequency limit applicability for the diode.

The classical definition of the Q of any device or circuit is

$$Q = \frac{\text{Energy Stored}}{\text{Energy Dissipated}}$$

For a capacitor, two equivalent circuits are possible.

Series



$$Q = \frac{1}{(2\pi) f R_S C}$$

Parallel



$$Q = (2\pi) f R_P C$$

Clearly, the two definitions must be equal at any frequency, which establishes

$$R_P = \frac{1}{(2\pi f)^2 C^2 R_S}$$

In the case of a high Q tuning diode, the better physical model is the series configuration, for the depleted region is an almost perfectly pure capacitance; and the undepleted region, due to its relatively low resistivity, is almost a pure resistor in series with the capacitance. Furthermore, the contact resistances are also clearly in series.

Q, then, for a tuning varactor is given by

$$Q_{(-V)} = \frac{1}{2 \pi f R_{(-V)} C_{(-V)}}$$

where  $f$  is the operating frequency,  $C_V$  is the junction capacitance, and  $R_V = R(\text{epi}) + R_C$ , the sum of the resistance of the undepleted epi and the fixed contact resistance.

From the above equation it follows that  $Q$  is a sensitive function of the applied reverse bias. As this bias is increased, epi depletion expands, reducing the junction capacitance as well as the undepleted epi resistance. Both of these changes translate into an increase in  $Q$ .

Also important to note is the dependence of  $Q$  on the operating frequency. Historically, the tuning varactor business developed the habit of specifying  $Q$  at 50 MHz, in spite of the fact that  $Q$  values of microwave diodes are so high that it is impossible to measure them accurately at 50 MHz. However, one may extrapolate  $Q$  to a different frequency simply by using the reciprocal relationship.

$$Q(f_1) = Q(f_2) \frac{f_2}{f_1}$$

The higher the  $Q$  factor of the varactor diode, the lower the energy dissipation and higher the operating frequency limit of the LC circuit in which it is used. There are two empirical rules developed by circuit designers that determine the frequency limits in two applications.

In voltage controlled oscillators, the maximum frequency of operation is approximately the one at which the varactor  $Q$  drops to 10

$$f_{\text{max limit}} = \frac{Q_{\text{ref}} f_{\text{ref}}}{10}$$

where  $Q_{\text{ref}}$  is the varactor  $Q$  measured at the reference frequency  $f_{\text{ref}}$ .

In tunable filters, the maximum frequency of operation is approximately the one at which the varactor  $Q$  drops to 100.

$$f_{\text{max limit}} = \frac{Q_{\text{ref}} f_{\text{ref}}}{100}$$

$Q_{\text{ref}}$  and  $f_{\text{ref}}$  have the same meaning as above.

The varactor  $Q$  is also a sensitive function of the temperature. In a well-constructed varactor diode

$$Q = T^{\frac{-3}{2}}$$

where  $T$  is the absolute temperature in degrees K. It follows from this equation that as temperature increases, the circuit losses increase and the frequency limitation becomes more severe. This relationship is particularly important to note when the operating temperature range extends well above the ambient temperature at which the  $Q$  values are measured and specified. A varactor selection based on its reported  $Q$  at ambient temperature may prove incorrect if its  $Q$  falls below the acceptable limit at the operating temperature.

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