February, 2007

Tackle wideband RF switching with PIN diodes

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Available at: https://works.bepress.com/chin-leong_lim/27/
Both bulk and Epi PIN diodes can satisfy RF-switching applications with their fast response times, long lifetimes, high linearity, and the simplified cascading of switches.

Costly mechanical switches can be justified when used in precision test equipment, such as vector network analyzers. For mass-produced consumer products like cable- or satellite-television (CATVISATV) delivery systems, however, less-expensive electronic switches are a better fit. These switches are based on either transistors or PIN diodes. The semiconductor switches have no moving parts. As a result, they provide faster response times and longer life spans than their mechanical counterparts.

PIN diodes are often employed as the switching elements in single-pole, single-throw (SPST) and single-pole, multiple-throw configurations. The PIN diode behaves like a current-controlled resistor to all signals higher in frequency than 10 times the cutoff frequency \( f_c \) of the diode, given by:

\[
f_c = \frac{1}{2\pi f_T}
\]

where \( f_T \) is the minority carrier lifetime.

The PIN diode's junction resistance, \( R_j \), can be changed from high to low by the application of a forward bias current. In addition, PIN diodes can be used in either series or shunt switching mode. The series-connected switch has an insertion loss, \( A \), corresponding to:

\[
A = 20\log\left(1 + \frac{R_j}{2Z_0}\right)
\]

In the shunt connection, the insertion loss becomes:

\[
A = 20\log\left(1 + \frac{Z_0}{2R_j}\right)
\]

where \( Z_0 \) is the characteristic impedance (typically 50 or 75 \( \Omega \) in RF transmission systems).

The selection of a switch topology requires a trade-off between bandwidth and isolation requirements. Although a series switch has the benefit of low-loss transmission over a very wide frequency range, it also has poorer isolation. Shunt switches are usually used in conjunction with quarter-wave transmission lines, which are inherently narrowband. Compared to the series connection, however, these transmission lines provide superior isolation.

Both test instruments and CATVISATV equipment demand RF switches that are capable of multi-octave operation without significant signal loss. A multi-carrier environment like CATVISATV imposes a stringent linearity demand on the switch. It must not introduce excessive distortion that could
packages. Electrical connections were made using the same wire-bonding profile.

The two different PIN diodes were then tested for insertion loss (IL), isolation (ISO), and third-order intercept (IP₃)—the parameters that are crucial to operation in wideband RF switching.

To prevent degradation in the signal-to-noise ratio, a series switch should have low insertion loss. This factor is especially critical in a weak-signal-reception system. Below 1 GHz, the diode switch’s reactive components do not have a significant impact on the IL. This parameter is primarily dictated by the equivalent series resistance, Rₛ. Within the boundary of the diode’s safe operating limits, it is possible to reduce the IL and Rₛ by increasing the bias current. The upper operating frequency limit is determined largely by the package’s parasitic inductance, which causes a rapid worsening of the IL above 2 GHz.

Generally, the Epi PIN diode has a lower IL than the bulk type at a given value of Iᵣ. In this comparison, the thin bulk diode needed approximately four times higher bias current than the Epi diode (20 mA vs. 5 mA) to achieve the same IL (Fig. 2 and Fig. 3).

In a series switch, the maximum usable frequency is determined by the decreasing isolation with frequency. The package and junction capacitances (Cₛ and Cₖ) allow higher frequencies to bypass the unbiased PIN diode’s high-junction resistance. At the low-frequency end, the bulk PIN diode exhibits better isolation than the Epi PIN diode because of the former’s higher resistance at zero bias (Fig. 4).

Of course, semiconductor switches do have an Achilles Heel: applications that combine multi-octave bandwidths and multiple carriers (not to mention systems requiring high-power handling). Junction nonlinearity creates even- and odd-order in-band distortion products that are impossible to filter in CATV networks. By comparison, mechanical switches generate inconsequentially small amounts of distortion under similar conditions. The low-band VHF channels (70 to 100 MHz), for example, generate second harmonics that can interfere with the high-band VHF channels (107 to 170 MHz). Generally, PIN-diode switches are more linear than transistor-based switches.²

In the forward-biased PIN diode, harmonic and intermodulation distortion are created by the modulation of the 1-layer charge density by RF currents. The distortion is influenced by frequency, stored charge, and junction resistance.³ The intercept point (IP₃) allows a widely used figure of merit for switch...
world, SPICE. SPICE has no provision for minority carrier lifetime, \( \tau \), which is an important PIN-diode parameter. As a workaround, the PIN-diode chip can be modeled as a simple linear circuit consisting of two resistors—one fixed and one variable—and one capacitor, as shown in Fig. 1.

The diode chip's current-dependent junction resistance can be approximated by:

\[
R_j = \frac{A}{I_f} k
\]

where \( I_f \) is the forward bias current in mA.

The parameters \( A \) and \( K \) are constants that are obtained from curve-fitting the previous equation against the graph of the measured RF resistance versus forward bias current, \( I_f \). An RF inductance-capacitance-resistance (LCR) bridge (e.g., the Agilent 4286A with the optional external bias accessory) provides a convenient and repeatable way to make this measurement. \( R_{\text{min}} \) and \( R_{\text{max}} \) represent the chip's contact and zero bias resistances, respectively. They are estimated from the minimum and maximum RF resistance shown on the aforementioned graph. In a packaged part, the diode-chip capacitance, \( C_p \), can only be obtained by indirect inference. First, the zero-bias capacitance is measured at a low frequency (typically 1 MHz). As a result, the reactance of the package's parasitic inductance, \( L_p \), becomes negligible. Subsequently, subtracting the package capacitance, \( C_p \), from the measured zero bias capacitance gives \( C_{\text{chip}} \). Usually, the diode manufacturer can provide these statistical data based on large sample sizes. The circuit designer is then spared much effort in extracting the parameters.

For this investigation, a bulk PIN diode (Avago HSMP-386Z, \( w = 22.5 \mu m \), \( \tau = 300 \) ns, and \( f_c = 0.3 \) MHz) was compared with an Epi PIN diode (Avago HSMP-389Z, \( w = 6.5 \mu m \), \( \tau = 180 \) ns, and \( f_c = 0.8 \) MHz). Although there are bulk diodes with thicker I regions than the above example, their disproportionately higher turn-on current makes them more suited to attenuator rather than switch applications. The diode chips were packaged in similar SOD-323...
the bulk diode's thicker I-layer permits operation at a lower frequency than the Epi diode.

**PIN-DIODE MODEL**

Parasitic circuit elements (such as unwanted inductances and capacitances), which are inherent in both the diode chip and package, define the limits of switch performance. Within the confines of series-switch configuration, both package and die capacitance ($C_p$ and $C_d$, respectively) combine to create a gradual degradation of isolation with increasing frequency. The package parasitic inductance, $L_p$, causes the switch's insertion loss to increase proportionately with frequency (Fig. 1). To improve the PIN-diode performance in the microwave region, manufacturers are constantly inventing smaller packages. These packages work to minimize parasitics. The industry-standard SOT-323, SOD-323, and SOD-523 are reflections of the never-ending impetus to produce lower-parasitic PIN-diode parts in low-cost plastic packages.

Unfortunately, the PIN diode cannot be modeled on the ubiquitous workhorse of the computer-aided-design (CAD)
Design Feature

to interference between channels. 

To improve the isolation compared to a single PIN diode, two or more PIN diodes can be connected in series. This series connection also allows the sharing of the same bias current in order to serve power. The beauty of a two-terminal switching element, such as the PIN diode, lies in the ease with which additional diodes can be cascaded in series. In contrast, the three-terminal transistor requires duplication of the control lines for each additional series switch element.

In contrast, the I-layer of the Epi diode is highly doped. The Epi diode is well suited for low-current RF switching in current-constrained products. The carrier lifetime is much shorter (τ = 5 - 300 ns). Unfortunately, this difference makes the epitaxial PIN diode much poorer in linearity than the bulk diode. As the linearity of PIN diodes generally deteriorates at low bias currents, this aspect practically rules out the Epi diodes from consideration as attenuators.

As previously mentioned, τ also determines the PIN switch's lower-frequency limit of usability due to its relation to the cutoff frequency, f_c. Below 10 times the cutoff frequency, the PIN diode no longer behaves like a current-controlled resistor. When

$$f < \frac{f_c}{10}$$

the diode's behavior is unpredictable. It alternates between a current-controlled inductor and capacitor. If the frequency is further lowered to

$$f < \frac{f_c}{10}$$

the PIN junction of the diode acts as a conventional PN junction. In general,
linearity, is a fictitious point where the linear transfer function intersects with the power of the intermodulation product. Third-order intermodulation products, $2f_1-f_2$ and $2f_2-f_1$, are considered the most troublesome because they occur close to the desired signal. The third-order intercept point (IP$_3$) of the PIN switch can be analyzed using the method of Caverly and Hiller$^4$:

$$IP_3 = 24 + 15 \log \frac{f \tau}{I_f}$$

where $f$ is in MHz, $I_f$ is in A, and $\tau$ is in ns.

In field-effect transistors (FETs), which form a competing switch technology, the distortion characteristic cannot be changed by varying bias. The PIN switch therefore holds an obvious advantage, as it can raise the IP$_3$ substantially with a small increase in bias current. Measurement of the PIN diodes' IP$_3$ showed a reasonably good agreement with the predicted values (Fig. 5).

In conclusion, both bulk and Epi PIN diodes offer different properties that suit them for different niches in RF switching. The RF switches used in CATV systems are fine examples of stringent requirements for wide bandwidth and low cost. Compared to FET- or CMOS-based switches, PIN-diode switches have the advantage of higher linearity, which is especially critical in a multi-carrier environment. They also promise ease in cascading additional switches in series without the need to duplicate control lines. Being two-terminal devices, PIN diodes also are less complicated to model in simulators.

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