A comparison of Bulk and Epitaxial PIN diodes in low cost wideband RF switching

By Lim Chin-Leong

White Paper

I. INTRODUCTION

Both electromechanical and semiconductor switches are proven technologies used in the control and routing of RF signals. The use of mechanical switches can be justified in precision test equipment, such as vector network analyzers. However, mass-produced consumer products with size and cost constraints, such as cable or satellite television (CATV/SATV) delivery systems, call for electronic switches based on either transistors or PIN diodes. The absence of moving parts also gives semiconductor switches the advantages over their mechanical counterparts of faster response times and longer life spans.

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

$f_c = 1/(2\pi\tau)$, where τ is the minority carrier lifetime.

The PIN diode's junction resistance, Rj, can be changed from high to low by applying a forward bias current. PIN diodes can be used either in series or shunt switching mode. The series connected switch has an insertion loss, A, corresponding to:

$$A = 20\log\left\{1+\frac{Rj}{2Zo}\right\}$$

In the shunt connection, the insertion loss becomes:[1]

$A = 20\log\left\{1+\frac{Zo}{2Rj}\right\}$, where Zo is the characteristic impedance (typically 50 or 75Ω in RF transmission systems).

The choice of switch topology is a tradeoff between bandwidth and isolation requirements. A series switch has the benefit of low loss transmission over a very wide frequency range, but has poorer isolation. Shunt switches are usually used in conjunction with quarter wave transmission lines that are inherently narrowband, but provide superior isolation compared to the series connection.

II. APPLICATION BACKGROUND

RF switches capable of multi-octave operation without significant signal loss are required in both test instruments and CATV/SATV equipment. A multi-carrier environment like CATV/SATV imposes a stringent linearity demand on the switch. It must not introduce excessive distortion that could lead to interference between channels, resulting in the degradation of signal quality.

Two or more PIN diodes can be connected in series to improve the isolation, compared to a single PIN diode. The series connection also allows the sharing of the same bias current to conserve power. The beauty of a two terminal switching element like 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.

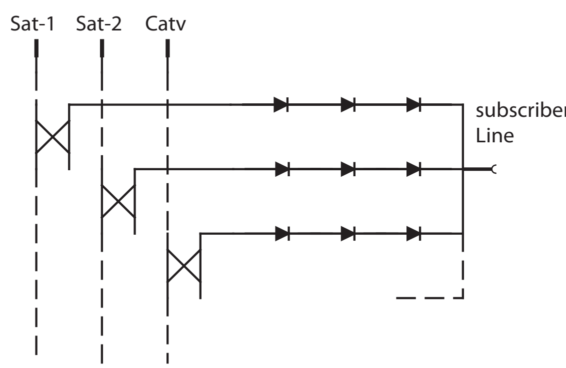

Figure 1. Typical switching circuit in a residential type CATV/SATV distribution network.

III. DIFFERENCES BETWEEN BULK AND EPITAXIAL PIN

Circuit designers need to distinguish between bulk and epitaxial (Epi) types of PIN diodes (Fig. 2). The two methods of constructing PIN diodes result in significant differences in RF behavior and, consequently, suitability for differing applications.

Bulk diodes have a low doping density in the substrate, requiring a high bias current to turn on. This makes the bulk PIN diode generally unsuitable for portable and other battery operated applications. Its very thick and pure I-layer produces a long carrier lifetime, τ of 300 ~ 3000 ns, which is an essential parameter for low distortion performance in both switch and attenuator applications.

In contrast, the I-layer of the Epi diode is highly doped. The Epi diode is eminently 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 practically rules out 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, fc. Below 10 times the cutoff frequency, the PIN diode no longer behaves like a current controlled resistor.

When $\frac{fc}{10} < f < 10fc$, the diode's behavior is unpredictable, alternating between a current controlled inductor and capacitor. If the frequency is further lowered to $f < \frac{fc}{10}$, the PIN junction of the diode acts as a conventional PN junction. In general, the bulk diode's thicker I-layer permits operation at a lower frequency than the Epi diode.

IV. PIN DIODE MODEL

Parasitics, inherent in both the diode chip and package, define the limits of switch performance. Confining our discussion to the series switch configuration, both package and die capacitance (C_p and C_j, respectively) combine to create a gradual degradation of isolation with increasing frequency. The package parasitic inductance, L_p (see Fig. 3), causes the switch's insertion loss to increase proportionately with frequency. To improve the PIN diode performance in the microwave region, manufacturers are constantly inventing smaller packages 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.

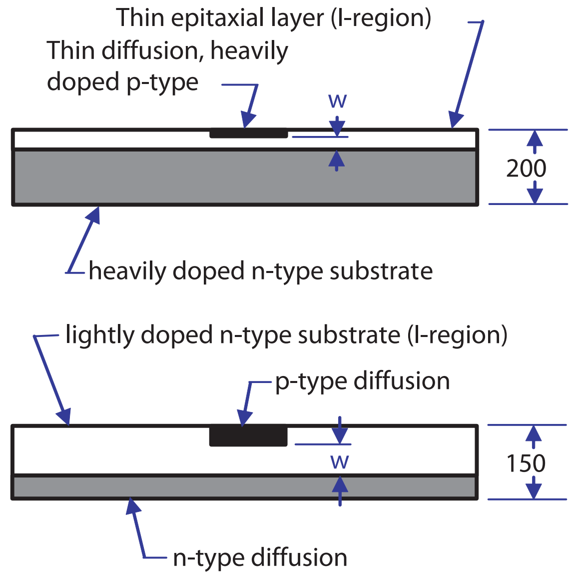

Figure 2. Construction of epitaxial (top) and bulk (bottom) PIN diodes.

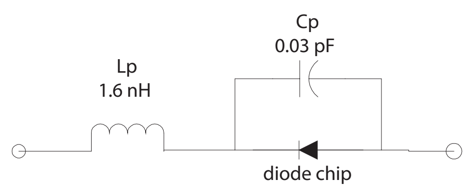

Figure 3. Equivalent circuit of the parasitics in the SOD-323 package.

Unfortunately, the PIN diode cannot be modeled on the ubiquitous workhorse of the CAD world, SPICE. The problem arises because SPICE has no provision for minority carrier lifetime, τ, 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. 4.

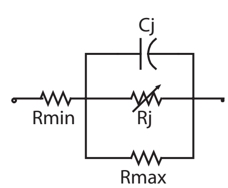

Figure 4. Linear equivalent circuit of the PIN diode chip.

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

$R_j = A / I_f^{\,K}$, where If is the forward bias current in mA.

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

V. RESULTS

For this investigation, a bulk PIN diode (Avago HSMP-386Z, w = 22.5 τ = 500 ns and fc = 0.3 MHz) was compared with an Epi PIN diode (Avago HSMP-389Z, w = 6.5 τ = 200 ns and fc = 0.8 MHz). There are bulk diodes with thicker I regions than the above example, but their disproportionately higher turn-on current make them more suited to attenuator rather than switch applications. The diode chips were packaged in similar SOD-323 packages and 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 (IP_3), the parameters crucial to operation in wideband RF switching.

A series switch should have low insertion loss (IL) to prevent degradation in signal to noise ratio, this being 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 being primarily dictated by the equivalent series resistance, R_S. 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 If. 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.

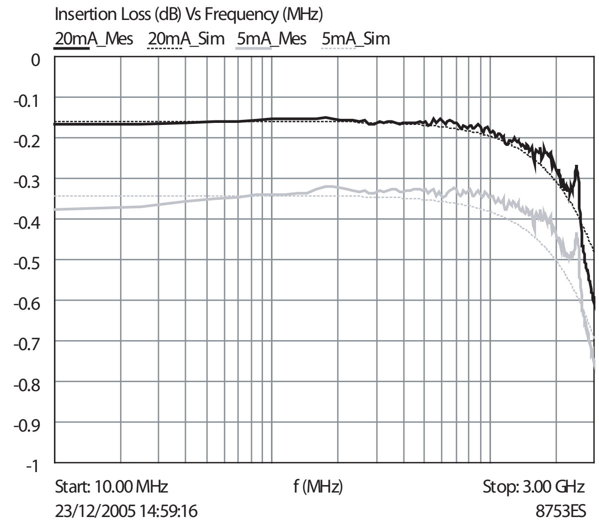

Figure 5. Simulated and measured insertion loss (dB) vs. frequency as a function of If (20 and 5 mA) of a bulk PIN diode (w=22.5 µ and τ=500 ns) in a SOD-323 package.

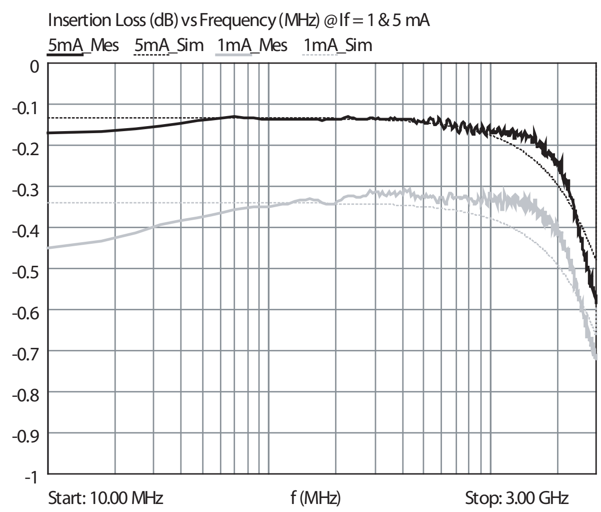

Figure 6. Simulated and measured insertion loss (dB) vs. frequency as a function of If (5 mA and 1 mA) of an Epi PIN diode (w=6.5 µ and τ=200 ns) in a SOD-323 package.

In a series switch, the maximum useable frequency is determined by the decreasing isolation with frequency. The package and junction capacitances (C_p and C_j) 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 its higher resistance at zero bias.

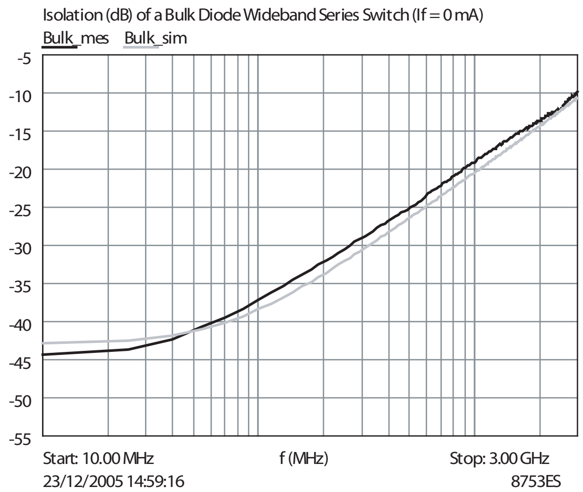

Figure 7. Simulated and measured switch isolation (dB) vs. frequency of a thin bulk diode in an SOD-323 package.

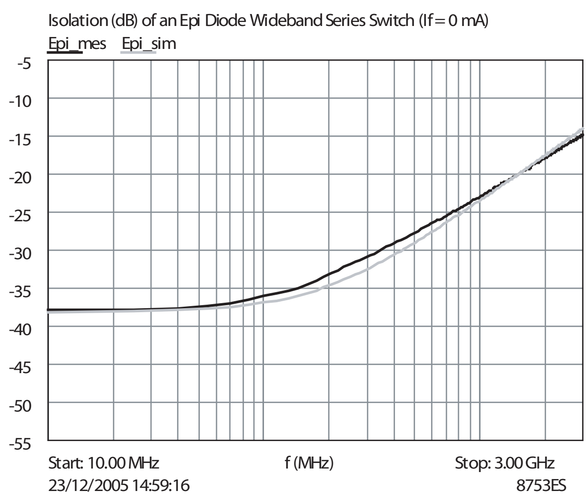

Figure 8. Simulated and measured switch isolation (dB) vs. frequency of an Epi diode in an SOD-323 package.

Applications combining multi-octave bandwidths and multiple carriers are the Achilles heel of semiconductor switches. 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. For example, the low band VHF channels (70 to 100 MHz) 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 I-layer charge density by RF currents. The distortion is influenced by frequency, stored charged, and junction resistance.[3] The intercept point (IPn), a widely used figure of merit for switch linearity, is a fictitious point where the linear transfer function intersects with the power of the intermodulation product. Third order intermodulation products, 2f1-f2 and 2f2-f1, are considered the most troublesome as they occur close to the desired signal. The third order intercept point (IP3) of the PIN switch can be analyzed using the method of Caverly and Hiller:[4]

$$IP_3 = 21 + 15\log \frac{f I_f \tau}{R_s}$$

Where, f is in MHz and τ is in ns.

It is worth noting that in field-effect transistors (FETs), a competing switch technology, the distortion characteristic cannot be changed by varying bias. This means that the PIN switch holds an obvious advantage in the ability to raise the IP3 substantially by a small increase in bias current. Measurement of the PIN diodes' IP_3 showed a reasonable agreement with the predicted values.

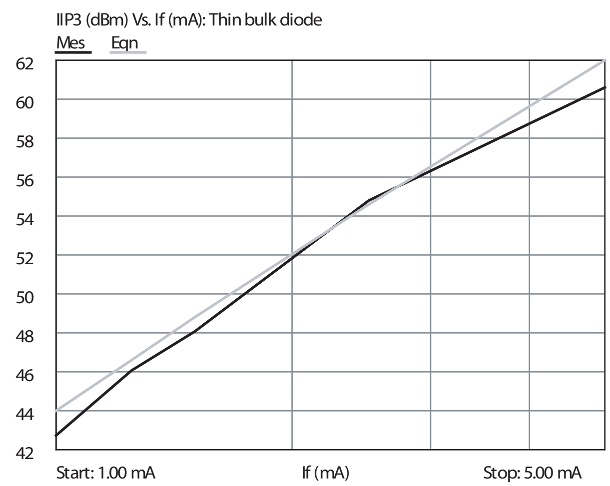

Figure 9. Measured and simulated third-order input intercept point vs. forward bias of a bulk PIN diode (w = 22.5 μ and τ= 500 ns)

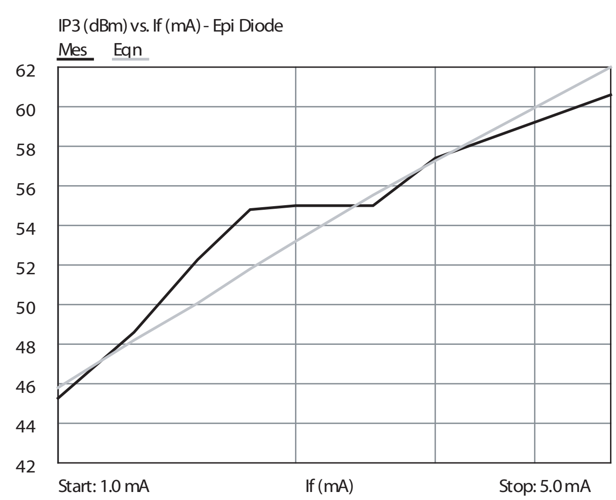

Figure 10. Measured and simulated third-order input intercept point vs. forward bias of an Epi diode (w=6.5 μ and τ =200 ns)

VI. CONCLUSION

Both bulk and Epi PIN diodes offer different properties, making them suitable for different niches in RF switching. RF switches used in CATV systems is one example with stringent requirements for wide bandwidth and low cost. Compared to FET- or CMOS-based switches, PIN diode switches have two important advantages:

a. higher linearity—especially critical in a multi-carrier environment.

b. ease of cascading additional switches in series without the need to duplicate control lines.

Being two terminal devices, PIN diodes are also less complicated to model in simulators.

VII. ACKNOWLEDGEMENT

I would like to acknowledge my mentor, Ray Waugh, who continued to guide me even after his retirement. I am also grateful to my colleagues, Chong Wern Ian, Soon Chee Huei, Ho King Pieng, Alan Rixon, Ian Piper, and Robert Brophy for their assistance, encouragement, and constructive feedback.

VIII. REFERENCES

[1] B.L. Smith and M.H. Carpentier, *The Microwave Engineering Handbook*, Vol. 1, p. 199, Chapman & Hall, 1993.

[2] E. Higham, "Distortion in Voltage-Variable Attenuators," *Microwave Journal*, Dec. 1999.

[3] R. Caverly, "Distortion Modelling of PIN Diode Switches and Attenuators," *IEEE MTT-S Digest*, p. 957, 2004.

[4] G. Hiller and R. Caverly, "Predict intercept points in PIN-diode switches," *Microwaves & RF*, Jan. 1986.

AUTHOR

Lim, Chin-Leong
Wireless Semiconductor Division,
Avago Technologies (Malaysia)
11950 Bayan Lepas Free Industrial Zone
Penang, Malaysia
Email: chin-leong.lim@avagotech.com

For product information and a complete list of distributors, please go to our web site: **www.avagotech.com**

AV02-2386EN - March 19, 2010