

# Applications for the HSMP-3890 Surface Mount Switching PIN Diode

## Application Note 1072

### Introduction

The PIN diode is generally considered to behave like a current controlled RF variable resistor<sup>1</sup>. In the microwave frequency range, this simplification is generally quite accurate. However, in the RF frequency range (below 2 GHz), matters are much more complicated, and the incorrect choice of diode can produce disastrous results in terms of circuit performance.

The discussion which follows assumes that the reader has had some exposure to RF signal control using PIN diodes. If not, you may refer to Appendix A, "Back To Basics," at the end of this note.

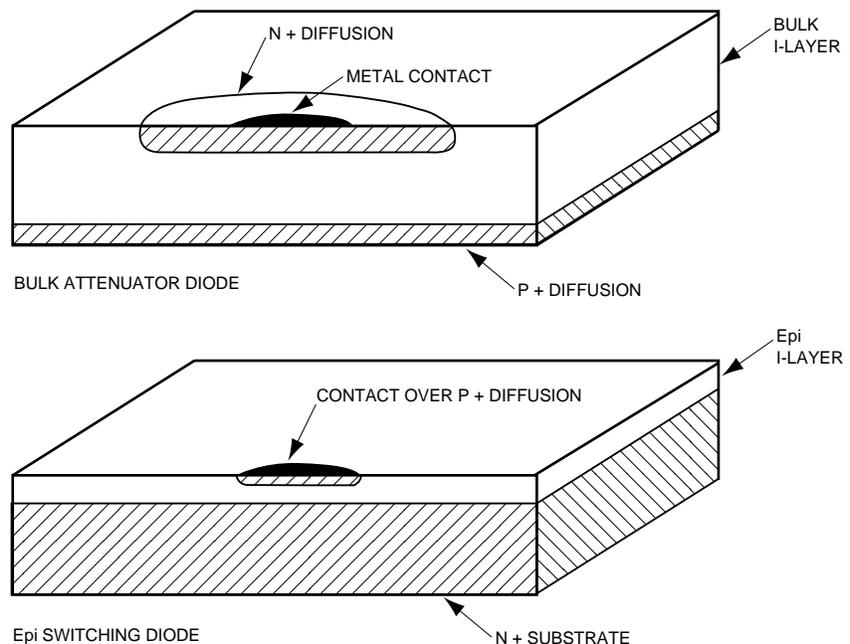
### PIN Diodes

In RF and microwave networks, mechanical switches and attenuators are bulky, often unreliable, and difficult to manufacture. Switch ICs, while convenient to use and low in cost in small quantities, suffer from poor distortion performance and are not as cost-effective as PIN diode switches and attenuators in very large quantities. For over 30 years, designers have looked to the PIN diode for high performance/low

cost solutions to their switching and level control needs.

In the RF and microwave ranges, the switch serves the simple purpose which is implied by its name; it operates between one of two modes, ON or OFF. In the ON state, the switch is designed to have the least possible loss. In the OFF state, the switch must exhibit a very high loss (isolation) to the input signal, typically from 20 to 60 dB. The attenuator, however,

serves a more complex function. It provides for the "soft" or controlled variation in the power level of a RF or microwave signal. At the same time as it attenuates the input signal to some predetermined value, it must also present a matched input impedance (low VSWR) to the source. Every microwave network which uses PIN diodes (phase shifter, modulator, etc.) is a variation on one of these two basic circuits.



**Figure 1.**

1. Hewlett-Packard Application Note 922, *Application of PIN Diodes.*

One can see that the switch and the attenuator are quite different in their function, and will therefore often require different characteristics in their PIN diodes. These properties are easily controlled through the way in which a PIN diode is fabricated. See Figure 1.

### Diode Construction

At Hewlett-Packard, two basic methods of diode fabrication are used. In the case of bulk diodes, a wafer of very pure (intrinsic) silicon is heavily doped on the top and bottom faces to form P and N regions. The result is a diode with a very thick, very pure I region. The epitaxial layer (or EPI) diode starts as a wafer of heavily doped silicon (the P or N layer), onto which a thin I layer is grown. After the epitaxial growth, diffusion is used to add a heavily doped (N or P) layer on the top of the epi, creating a diode with a very thin I layer populated by a relatively large number of imperfections.

These two different methods of design result in two classes of diode with distinctly different characteristics, as shown in Table 1.

As we shall see in the following paragraphs, the bulk diode is almost always used for attenuator applications and sometimes as a switch, while the epi diode (such as the HSMP-3890) is generally used as a switching element.

### Diode Lifetime and Its Implications

The resistance of a PIN diode is controlled by the conductivity (or resistivity) of the I layer. This conductivity is controlled by the density of the cloud of carriers (charges) in the I layer (which is, in turn, controlled by the DC bias). Minority carrier lifetime, indicated by the Greek symbol  $\tau$ , is a measure of the time it takes for the charge stored in the I layer to decay, when forward bias is replaced with reverse bias, to some predetermined value. This lifetime can be short (35 to 200 nsec. for epi diodes) or it can be relatively long (400 to 3000 nsec. for bulk diodes). Lifetime has a strong influence over a number of PIN diode parameters, among which are distortion and basic diode behavior.

To study the effect of lifetime on diode behavior, we first define a cutoff frequency  $f_c = 1/\tau$ . For short lifetime diodes, this cutoff frequency can be as high as 30 MHz while for our longer lifetime diodes  $f_c > 400$  KHz. At frequencies which are ten times  $f_c$  (or more), a PIN diode does indeed act like a current controlled variable resistor. At frequencies which are one tenth (or less) of  $f_c$ , a PIN diode acts like an ordinary PN junction diode. Finally, at  $0.1 f_c \leq f \leq 10 f_c$ , the behavior of the diode is very complex. Suffice it to mention that

in this frequency range, the diode can exhibit very strong capacitive or inductive reactance — it will not behave at all like a resistor. However, at zero bias or under heavy forward bias, all PIN diodes demonstrate very high or very low impedance (respectively) no matter what their lifetime is.

### Diode Resistance vs. Forward Bias

If we look at the typical curves for resistance vs. forward current for bulk and epi diodes (see Figure 2), we see that they are very different:

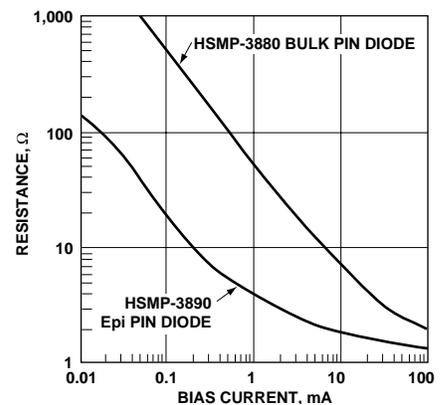


Figure 2. Resistance vs. Bias Current, Hewlett-Packard PIN Diodes

Of course, these curves apply only at frequencies  $> 10 f_c$ . One can see that the curve of resistance vs. bias current for the bulk diode is much higher than that for the epi (switching) diode. Thus, for a given current and junction capacitance, the epi diode will always have a lower resistance than the bulk diode. The thin epi diode, with its physically small I region, can easily be saturated (taken to the point of minimum resistance) with very little current compared to the much larger bulk diode. While an epi diode is well saturated at currents around 10 mA, the bulk diode may require upwards of 100 mA or more. Moreover, epi diodes can achieve

Table 1. Bulk and EPI Diode Characteristics

Characteristic	EPI Diode	Bulk Diode
Lifetime	Short	Long
Distortion	High	Low
Current required	Low	High
I Region Thickness	Very thin	Thick

reasonable values of resistance at currents of 1 mA or less, making them ideal for battery operated applications.

Having compared the two basic types of PIN diode, we will now focus on the HSMP-3890 epi diode, the subject of this note.

Given a thin epitaxial I region, the diode designer can trade off the device's series resistance  $R_S$  and junction capacitance  $C_j$  by varying the diameter of the contact and I region. Hewlett-Packard produces two epi switching PIN diodes, the HSMP-3820 and the HSMP-3890. The former features very low  $R_S$ , making it suitable for high-Q applications such as band switching an oscillator's resonant circuit. However, its relatively high total capacitance (typically 0.75 pF) limits its performance in high frequency (UHF) switching applications. The HSMP-3890, however, was designed with the 930 MHz cellular and RFID, the 1.8 GHz PCS and 2.45 GHz RFID markets in mind. Combining the low resistance shown in Figure 2 with a typical total capacitance of 0.27 pF, it forms the basis for high performance, low cost switching networks.

### Single Diode Switches

In order to predict the performance of the HSMP-3890 as a switch, it is useful to construct a model which can then be used in one of the several linear analysis programs presently on the market. Such a model is given in Figure 3, where  $R_j > 3/I$  and  $I$  is the current in mA. This equation, of course, applies only for  $f > 10 f_c$ , or approximately 100 MHz.

It should be noted that nonlinear analysis programs such as SPICE

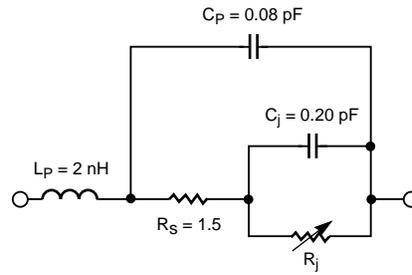


Figure 3. Model of Single Diode Switch.

lack a key parameter, carrier lifetime, in their diode model. Thus, they cannot be used to predict the performance of a circuit containing a PIN diode unless the diode is modelled as a resistor.

The HSMP-3890 can be used as a single switching element, either as a series or a shunt switch, as shown in Figure 4. We can simplify the model given in Figure 3 to achieve the equivalent circuits of the diode in the isolation mode (reverse bias for the series diode, forward bias for the shunt diode). These two equivalent circuits can then be analyzed to predict the isolation which either configuration will produce.

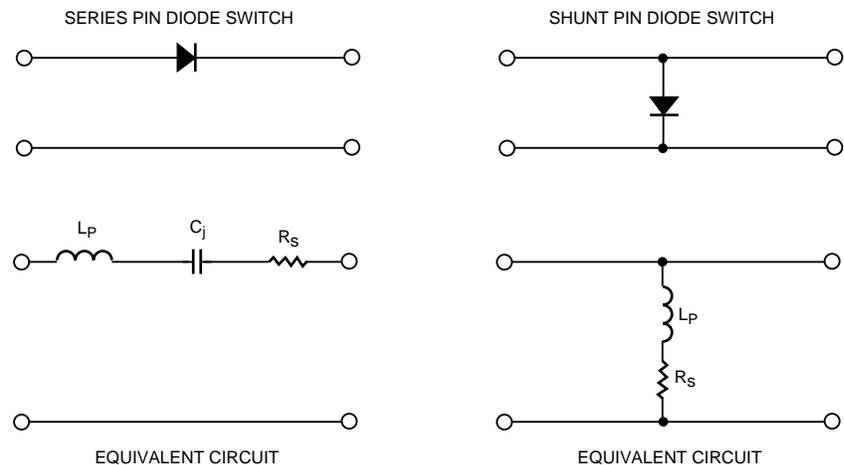


Figure 4. Series and Shunt PIN Diode Switches.

The circuits from Figure 4 were analyzed on AppCAD<sup>2</sup> with the results shown in Figure 5. It can be seen that the series diode switch provides higher isolation at any given frequency, which is a result of the high parasitic inductance of the SOT-23 package. Nevertheless, both configurations provide useful amounts of isolation at frequencies under 1 GHz.

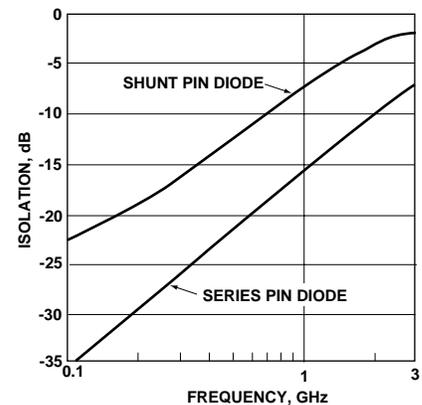


Figure 5. Isolation of a Single HSMP-3890 PIN Diode in a 50  $\Omega$  System.

2. AppCAD, an MS-DOS program available from your HP sales office.

## Multiple Diode Switches

For higher levels of isolation, there are a number of circuit design techniques which can be used.<sup>1,3</sup> The most useful of these is to cascade series and shunt diode switches, as shown in Figure 6, keeping the spacing between them small with respect to a wavelength. The resulting isolation, calculated using AppCAD, is dramatically higher than that produced by a single diode. This arrangement can be implemented with two HSMP-3890 diodes, or with the HSMP-3892 pair (also in the SOT-23 package).

If the series/shunt combination of Figure 6 is cascaded (using four diodes), the resulting isolation will be twice that of a single pair (40 dB instead of 20 dB, etc.).

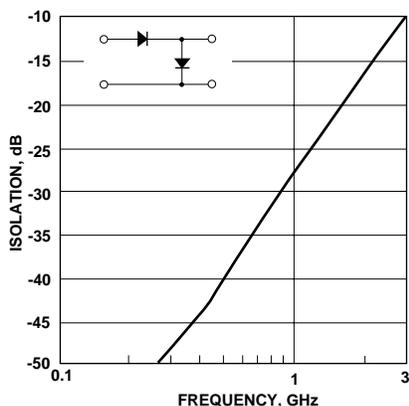


Figure 6. Isolation of a Series/Shunt pair of HSMP-3890 PIN Diodes in a 50  $\Omega$  System.

For the designer who wishes to use the shunt switch but needs more isolation, the low inductance HSMP-4890 can be used, as shown in Figure 7 (along with its equivalent circuit).

Other switch design approaches are given in the data sheet for the HSMP-389X series of switching PIN diodes.

Of course, the typical application of switching PIN diodes is multi-throw switches, rather than the SPST described above. While the single HSMP-3890 can be used with good results in multi-throw switches, the multi-diode products can offer savings in space, as illustrated in Figures 8 and 9.

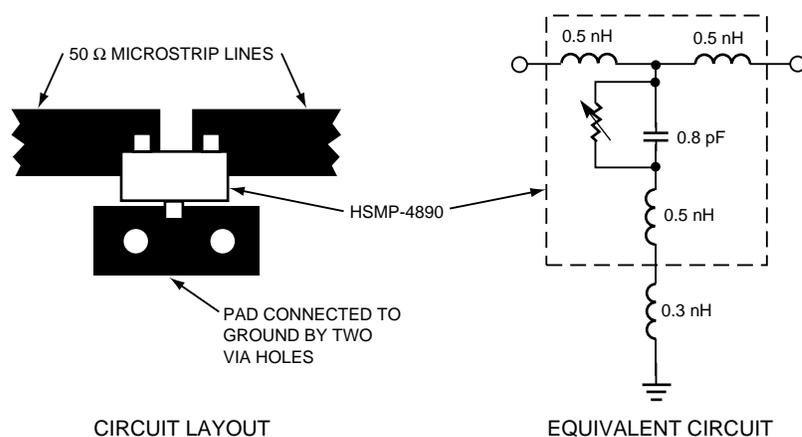


Figure 7.

3. R.W. Waugh and M.M. Waugh, "SPDT Switch Serves PCN Applications," *Microwaves & RF*, January, 1994.

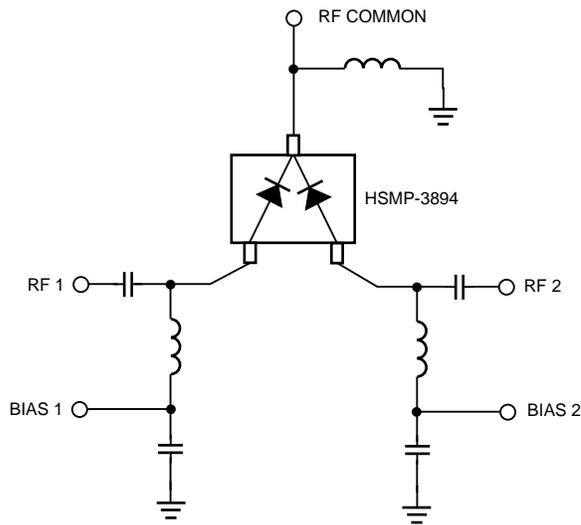


Figure 8. Simple SPDT Switch.

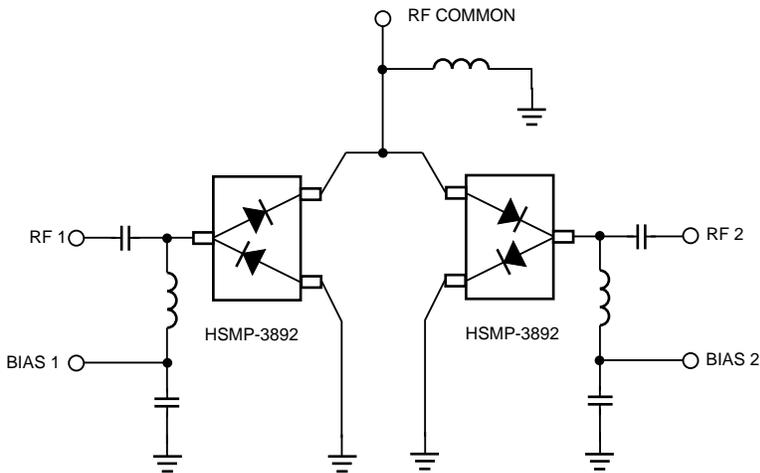


Figure 9. High Isolation SPDT Switch.

## Conclusion

The HSMP-3890 PIN diode has been described and shown to be an excellent choice for a high performance/low cost RF switch. For further information, contact your local HP sales office.

## Appendix A: Back to Basics

The most important property of the PIN diode is the fact that it appears as an almost pure resistance at RF (radio frequencies), whose resistance can be varied over a

range of approximately 1 to 10,000  $\Omega$  through the use of a DC (direct current) control current. When the control current is varied continuously, the PIN diode is useful for leveling and amplitude modulating an RF signal (operating as a so-called attenuator). When the control current is switched "on" and "off" or in discrete steps, the device is useful for switching (and other switch type functions, such as phase shifting, pulse modulating, etc.). The PIN diode's small size and weight, as well as its high switching speed and freedom from parasitic elements, make it ideally suited for use in miniature, broadband signal control components.

A PIN diode is a silicon semiconductor consisting of a layer of intrinsic (high resistivity) material of finite area and thickness which is contained between highly doped P and N type materials. When the diode is forward biased with DC current, charge is injected into this intrinsic or "I" region. This charge consists of holes and electrons which have a finite lifetime before they recombine. The density of charge in the intrinsic region, and its geometry, determine the conductance of the device. The lifetime (denoted by the Greek symbol  $\tau$  or "tau") determines the approximate low frequency limit of useful application, as well as other important parameters of the diode.