

Introduction

Silicon PIN diodes have been the most important semiconductor component used for the control of microwave signals for many years. Their major utilization has been for switching or variable attenuation elements to control R.F. power at frequencies from H.F. through millimeter frequency.

As systems requirements have placed increasing emphasis on extremely rapid switching, the ambipolar mobility of the Silicon material has placed limitations on switching speeds for Silicon PIN diodes. These limitations are presently in the range of a "few" nanoseconds for present "fast" Silicon PIN diodes. The major limitation for PIN switching speed is the removal of the charge or carriers used to produce a low impedance in forward bias. The charge removal is limited by the carrier mobility and the thickness of the I-layer necessary to support a moderate breakdown voltage (i.e., 30-100 volts).

Gallium Arsenide has several advantages over Silicon when making fast PIN diodes of similar dimensions. GaAs also has a few major disadvantages which limit the type of devices that can be produced. This paper will discuss these characteristics as they effect the type of GaAs PIN diode that can be built and the usage of GaAs PIN diodes in fast, moderate power switches.

Advantages

The advantages of Gallium Arsenide as a semiconductor material for PIN diodes are as follows:

1. The bandgap of Gallium Arsenide is larger than that of Silicon. This results in two key advantages:
 - (a) The breakdown voltage for the same intrinsic layer thickness is larger for GaAs PIN diodes than it is for Silicon PIN diodes. This enables the use of thinner, "faster" PIN diodes having the same reverse voltage.
 - (b) The higher bandgap of GaAs allows a higher impedance, (i.e., smaller capacitance at a small forward voltage). This allows GaAs PIN diodes to be driven directly from buffered TTL logic gates. (Most TTL logic circuits have a small residual voltage at the zero state. This is normally 0.2-0.3 volts). Such a positive "forward" bias voltage will "turn on" most Silicon PIN diodes and reduce their "off" impedance.
2. GaAs has direct minority carrier transition recombination. This normally limits "lifetime" to less than 10 nanoseconds. Limited "lifetime" results in fast removal of the charge.

Disadvantages

Some disadvantages of GaAs as a material for PIN diodes are as follows:

1. The material lifetime and available carrier diffusion length of Gallium Arsenide are 50 to 100 times less than that of Silicon. This severely limits the useful I-layer thickness of GaAs PIN diodes and their resulting breakdown voltages. The maximum useful breakdown voltage of GaAs PIN diodes is only about 150-250 volts. Useful Silicon PIN diodes can be built with breakdown voltage up to 4000-5000 volts.
2. The thermal resistance of GaAs is approximately three times that of Silicon. This limits the power that can be dissipated with GaAs PIN diodes.

The following section discusses these topics in greater detail.

A. PIN Diode Characteristics

The electrical characteristics of PIN diodes are primarily determined by the width and size of the I-layer. Figure 1 illustrates a stylized view of a PIN diode. The pertinent equations necessary to determine the capacitance, resistance and breakdown voltage of a PIN diode under both reverse and forward bias are shown (1).

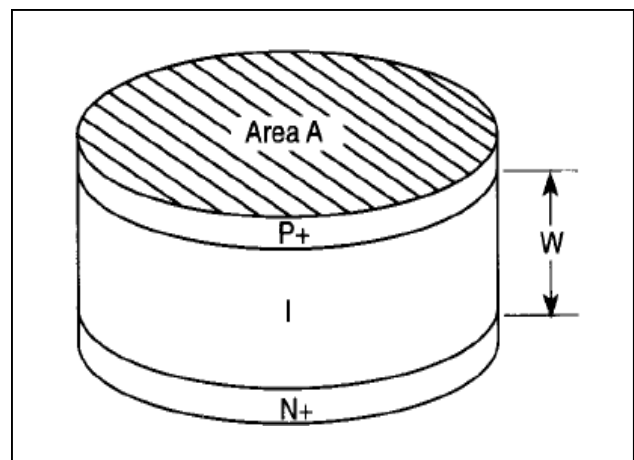


Figure 1. Pin Diode

Comparison of Gallium Arsenide and Silicon PIN Diodes for High Speed Microwave Switches

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RF Electrical Modeling of PIN Diode

Forward Bias Model

$$R_S = \frac{W^2}{(\mu_n + \mu_p) Q} \text{ (ohms)}$$

Where

$Q = I_F \chi \tau$ (coulombs)

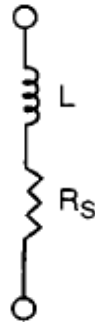
$W = I$ -region width

$I_F =$ forward bias current

$\tau =$ carrier lifetime

$\mu_n =$ electron mobility

$\mu_p =$ hole mobility



Notes:

1. In practical diode the parasitic resistance of the diode package and contact limit the lowest resistance value
2. The lowest impedance will be affected by the parasitic inductance, L , which is generally less than 1 nHy.
3. The equation is valid at frequencies higher than the I -region transit time frequency, i.e., $f > \frac{1300}{W^2}$ (where frequency is in MHz and W in μm).
4. The equation assumes that the RF signal does not affect the stored charge.

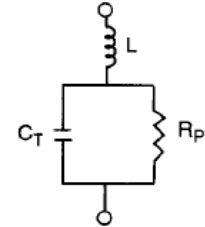
Zero or Reverse Bias Model

$$C_T = \frac{\epsilon A}{W}$$

Where

$\epsilon =$ dielectric constant of silicon

$A =$ area of diode junction



Notes:

1. The above equation is valid at frequencies above the dielectric relaxation frequency of the I -region, i.e. $f = \frac{1}{2\pi p}$ (where p is the resistivity of the I -region) At lower frequencies the PIN diode acts like a varactor.
2. The value of R_P is proportional to voltage and inversely proportional to frequency. In most RF applications its value is higher than the reactance of the capacitance, C_T , and is less significant.

Table 1

Table 1 shows the values of the physical constants of GaAs and Silicon. These physical properties determine the PIN diodes' RF characteristics (as previously shown).

Values of Material Constants for GaAs and Silicon PIN Diodes^{2,3}

Description	Symbol	GaAs	Silicon	Units
Breakdown Voltage of I-Layer	-	~18-25	~12-15	Voltage/ μmeter
Material Lifetime (Photogeneration)	τ	$\sim 10^{-9}$	$\sim 2 \times 10^{-4}$	Seconds
Electron Mobility Hole Mobility	μ_e μ_h	~5500 ~400	~1500 ~450	$\text{CM}^2/\text{V-s}$ $\text{CM}^2/\text{V-s}$
Ambipolar Mobility	μ	~800	~600	$\text{CM}^2/\text{V-s}$
Ambipolar Diffusion Constant	D_{ap}	~25-30	~15-16	CM^2/S
Maximum Diffusion Length	L	~10	~400-600	Microns
Relative Dielectric Constant	ϵ	~12.5	~11.8	-

B. Physical Limitations of GaAs and Silicon PIN Diodes

The major difference in Gallium Arsenide and Silicon material is that the carriers in GaAs recombine by direct transition recombination, while Silicon carrier recombination is normally through traps. The direct recombination process is much more rapid, resulting in short carrier lifetime.

Typical lifetimes for lightly doped, high resistivity ($N_d \sim 10^{10} - 10^{13}$ carrier/cc) GaAs and Silicon material are as follows:

GaAs (τ) = $\sim 5 \times 10^{-9}$ to 10^{-8} seconds

Silicon (τ) = $\sim 5 \times 10^{-3}$ to 2×10^{-4} seconds

The result of the different carrier lifetimes is that Silicon PIN diodes can have much longer diffusion lengths because:

$$(4) \quad L = \sqrt{D_{ap} \times \tau d}$$

Where

$D_{ap} =$ ambipolar diffusion constant

$\tau d =$ lifetime (diode)

(But it will not exceed the material lifetime).

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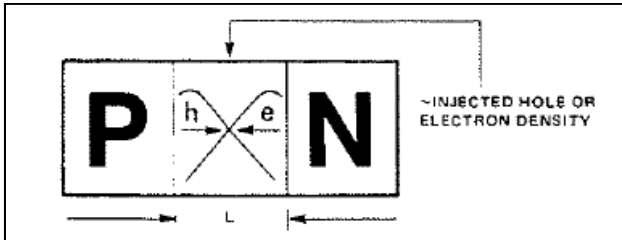
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The limiting diffusion lengths for GaAs or Silicon PINs are approximately as follows:

GaAs L ~ 10-20 micrometers (maximum)
 Silicon L ~ 400-600 micrometers (maximum)

If the PIN diode I-layer width is equal to or longer than the nominal carrier diffusion length, some of the injected carriers will recombine.

The average charge will be decreased and the series resistance will increase, i.e.



Figures 2 and 3 illustrate this effect in actual PIN diodes. Silicon PIN diodes with I-layer widths of 10-200 micrometers (100-2500 volts) have almost the same series resistance (as predicted by the model). The thick, 450 micrometer diodes, ~5000 volt diodes, begin to have higher series resistance. The same increasing series resistance trend is seen between 10-20 micrometers for a GaAs PIN diode. (Figure 3)

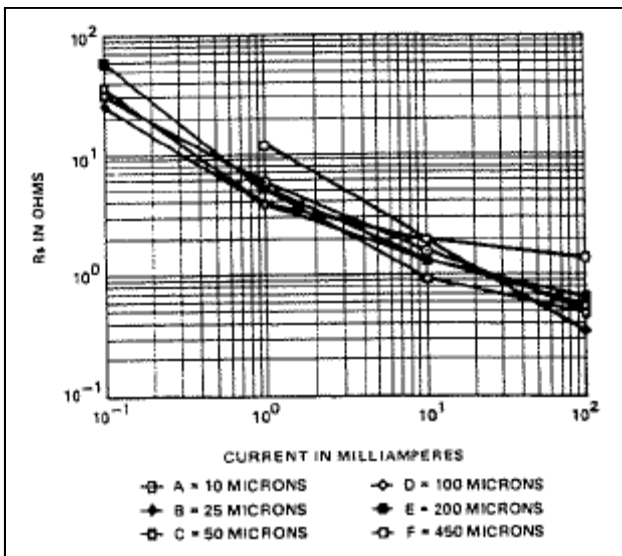


Figure 2. Series Resistance vs. Current for Different I-Layer Silicon PINs

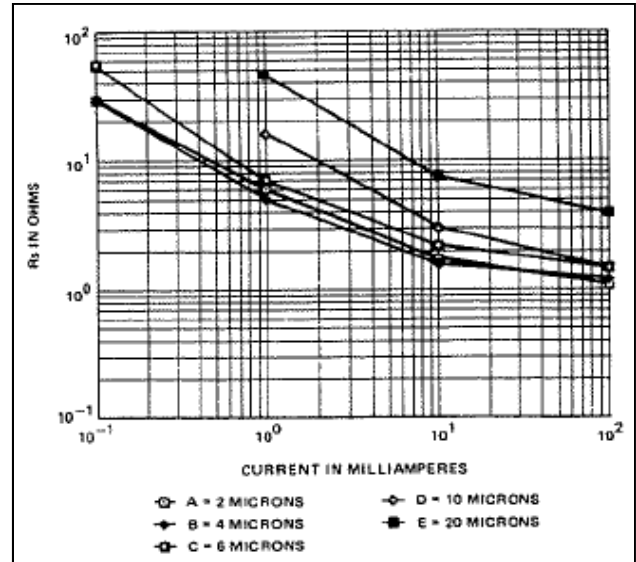


Figure 3. Nominal Series Resistance vs. Current for Different I-Layer Thickness GaAs PIN Diode of $C_1 \sim 0.5$ pF

The reverse voltage of a PIN diode is determined by the I-layer width and the avalanche breakdown field of the semi-conductor material. Breakdown voltage is approximated by:

$$(5) \quad V_b \approx \epsilon_m W$$

where:

W = I-layer width

ϵ_m = "Breakdown" field

GaAs $\epsilon_m \approx 18$ - volts/micron

Silicon $\epsilon_m \approx 10$ - 15 volts/micron

The previously discussed I-layer thickness limitation places an approximate maximum voltage limit on single junction diodes as follows:

GaAs ~ 150-250 volts

Silicon ~ 4000 - 6000 volts

C. Thermal Resistance and Power Dissipation

GaAs material has approximately three times the thermal resistance of Silicon. (3) The thermal resistance places a limitation on the power that may be dissipated in GaAs PIN diode.

Normally, fast switches are used in receivers or for local oscillator switching. Usually only low power is switched.

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The higher thermal resistance of a GaAs PIN diode is not a limitation for these applications. Figure 4 illustrates the difference in thermal resistance for small capacitance, GaAs PIN diodes and Silicon PIN diodes.

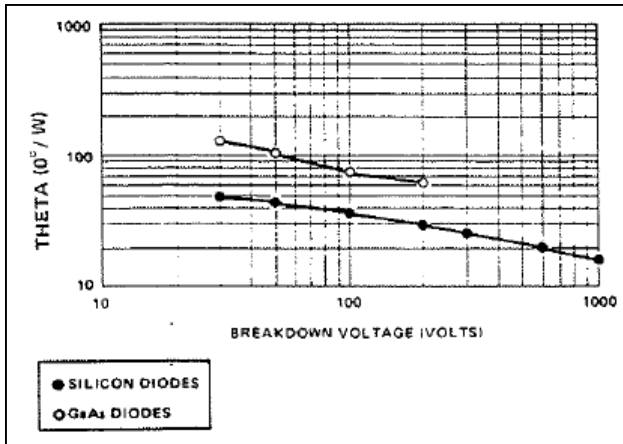


Figure 4. Comparison of the Thermal Resistance of 0.1 pF Capacitance GaAs and Silicon PINs vs. Breakdown Voltage

D. GaAs PIN Diode Driver Considerations

Because of higher bandgap and low I-layer intrinsic doping, GaAs PIN diodes can have higher impedance at a small forward voltage.

Figure 5 illustrates a stylized view of this concept. Figure 6 shows an actual C/V plot of three thin GaAs PIN diodes.

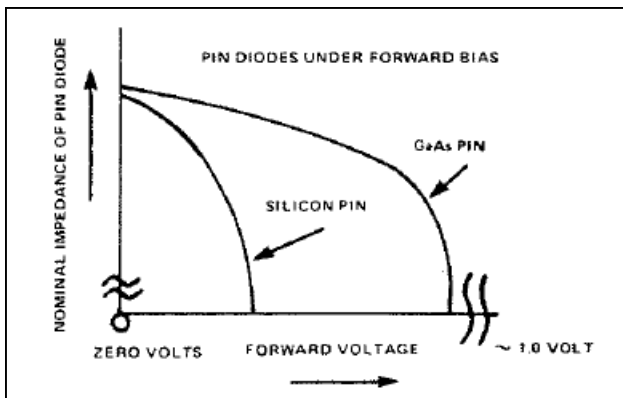


Figure 5. Stylized Impedance of GaAs and Silicon PINs

Note: GaAs PIN diodes can have high impedance at +0.3-0.5 volts forward bias.

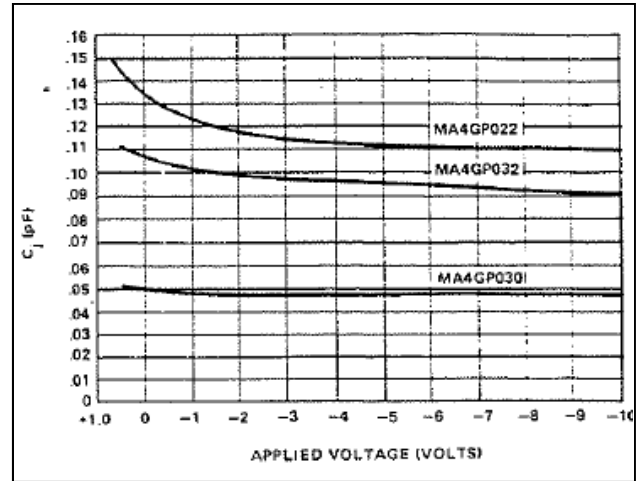


Figure 6. Capacitance Voltage Characteristics at 1 GHz

The higher the impedance at forward bias allows one to obtain good RF switching when driving a GaAs PIN diode from TTL logic. Such a logic driver is illustrated in Figure 7.

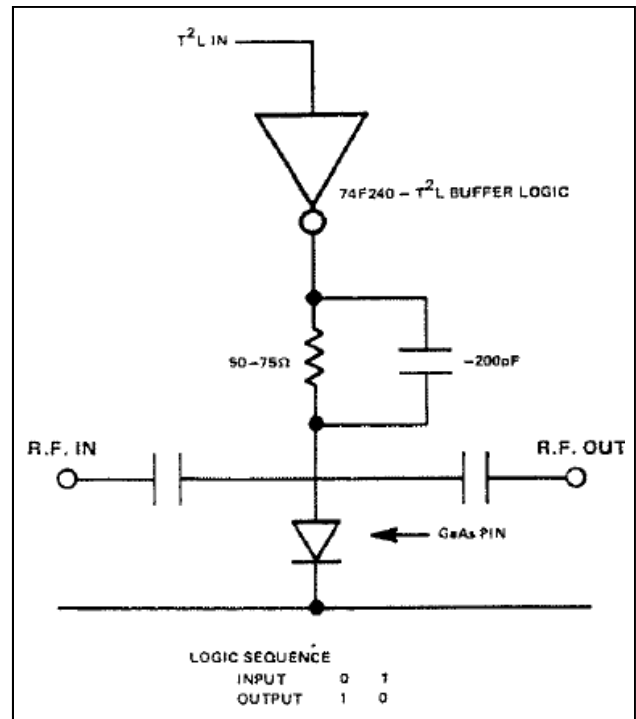


Figure 7. GaAs PIN Diode Switching Circuit

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Single pole, double throw switches can also be switched using simple "logic" gates. Figures 8 and 9 show the schematic of an inexpensive driver designed to use a TTL buffer and an inexpensive Nand buffer. It can drive a series/shunt GaAs PIN diode switch combination as described below:

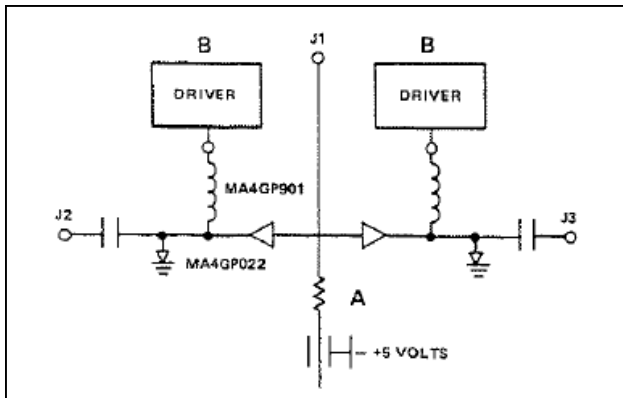


Figure 8. GaAs PIN SPDT Driver Circuit

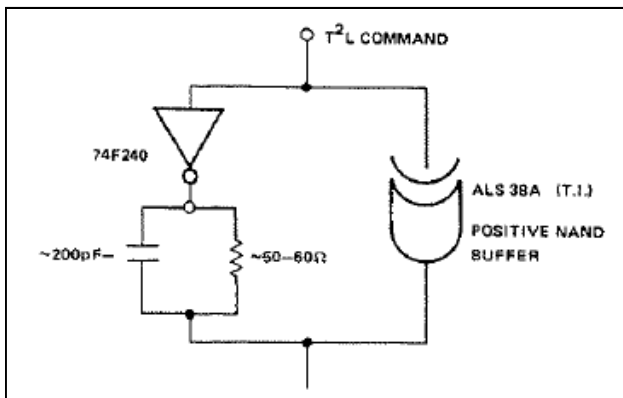


Figure 9. Driver Schematic

The common +5 volts supply is used to forward bias one or the other of the series diodes. The current should be controlled at the common input (A). A suitable current is approximately 5 to 20 mA. The forward bias diode will allow RF power to flow from J1 to either of the opposing arms (J2 or J3).

The driver connection (B) is a short at the TTL (one). This will zero bias the shunt diode and allow a low resistance "sink" for the series connected diode's current. (See driver schematic - Figure 9).

The "zero state" logic will cause current to pass through the ~ 50 ohm resistor (~10-20 mA) to forward bias the shunt diode. The voltage drop across the diode will zero or slightly reverse bias the series diode and shut it off. This arm will then isolate.

GaAs and Silicon PIN Diode Switching Times

The switching time of PIN diodes depends on the time required to remove or inject the charge. This required time is dependent on the I-layer thickness, carrier mobility and the resulting transit time (T_p).

Figures 10 and 13 show the nominal carrier transit time (T_p) and the achievable RF (transition) switching times for Silicon and GaAs PIN diodes (2).

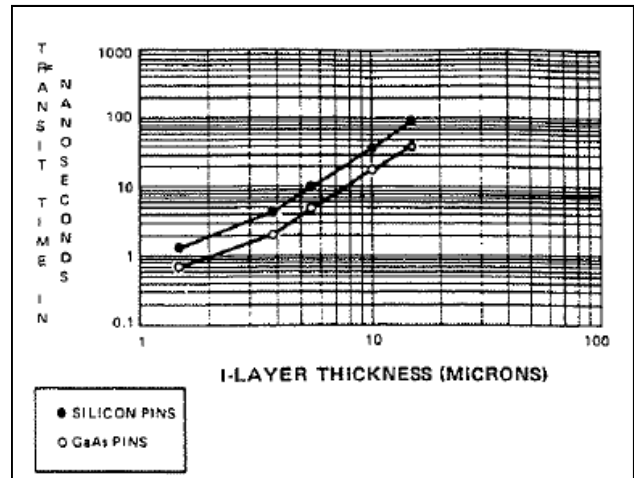


Figure 10. Transit Time (T_p) of GaAs and Silicon PINs vs. I-Layer Thickness in Micrometers

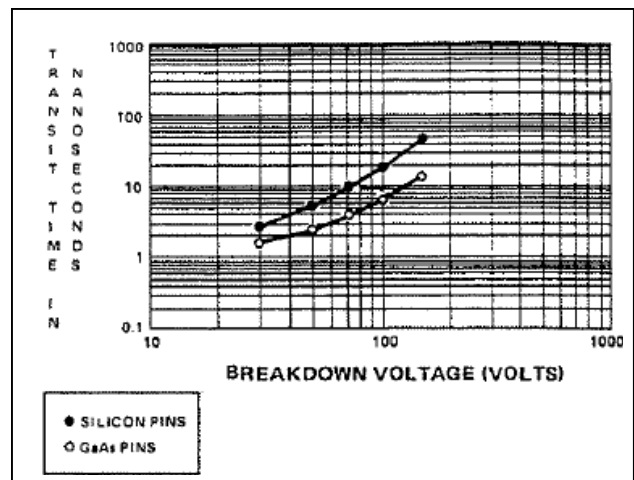


Figure 11. Transit Time (T_p) of GaAs and Silicon PINs vs. their Breakdown Voltage