Bulk Semiconductor Switches and Phase Shifters

K. E. Mortenson, J. F. White, A. Armstrong and J. Borrego
Rensselaer Polytechnic Institute, Troy, New York

Introduction

Both switches and phase shifters using PIN diodes have great appeal to the designers of electronically steered, phased array antennas. With the PIN diode, conductivity modulation of the intrinsic region to a low resistance is effected under forward bias by the injection of carriers from the P+ and N+ contacts. An RF sinusoidal voltage applied across the diode terminals sees an unvarying resistance, because no appreciable net carrier drift occurs in the brief duration of half an RF cycle.

In practice, filtering circuits are needed to separate the bias and RF signals outside of the diode. However, a major drawback of the two terminal PIN is the bound which its two terminal nature places on the amount of its semiconductor volume. The device thickness should be less than the carrier diffusion length for good conductivity modulation. The maximum area is then dictated, for a given thickness, by the tolerable RF capacitive susceptance in the microwave control network.

These limitations can be circumvented by making the bias and RF excitations of the semiconductor orthogonal to one another. Control elements with this feature are shown in Figures 1 and 2 for use in switches and phase shifters respectively. Such elements can be considered bulk control devices, since the RF signal is applied directly across an intrinsic semiconductor region. The conductivity of the semiconductor, typically silicon, is variable thru the bias. Ideally, the behavior of these waveguide elements varies between a capacitive obstacle with zero bias to a short circuit with the switch (or an inductive susceptance with the phase shifter) as forward bias is applied. The switchable susceptance function is particularly appropriate in the transmission type phase shifter circuit[1].

The Waveguide Window

The switch shown in Figure 1 functions as a variable conductivity aperture in the waveguide. Holes and electrons are injected from the line structures on the front and rear faces of the silicon "window" thereby regulating the amount of microwave propagation thru it. Specification of the processes needed to diffuse in and metal plate the injection structures is possible from the technology used for the conventional PIN diode. The remainder of the design consists of choosing the line spacing and thickness of the window such that a fairly homogeneous and low resistivity plasma is established in the intrinsic silicon under forward bias. This consideration is , in turn, based upon the bulk lifetime of the injected carriers and their surface recombination velocity.

One experimental model, constructed in quarter height S-band waveguide, used on each side 4 mil wide lines spaced on 10 mil centers for the bias injecting structures. The silicon slab, 8 mils thick, was cut from 2 kilohm-cm silicon with a bulk lifetime of about 500 microseconds. This device possessed an insertion loss variation of 0.5 to 8 decibels as the bias was changed from 0 to 20 amperes (delivered at 3 volts) respectively. The high loss state corresponds to an average conductivity modulation to about 5 ohm-cm whereas about 0.5 ohm-cm is needed for 20 db of isolation. The rather high value for achieved resistivity is attributable to a low value for the average lifetime realized. From measurements of the DC characteristic and transient recovery the effective lifetime is estimated at about 5 microseconds. If, arbitrarily, the spacing between injecting structures is required to be no more than twice the mean diffusion length, then the average lifetime should be in excess of 10 microseconds. Further experiments are underway to increase the realizable switch isolation.

A great advantage of these windows is their high power capability. Static tests made with windows uniformly doped to the required resistivities have shown that 150 kilowatt RF pulses of 1 microsecond and 0.001 duty cycle can be sustained with only a 50°C temperature rise. If realized, this power handling capability is more than an order of magnitude above that which would destroy a conventional PIN diode suitable for switching the 2.6-4.0 ghz. waveguide bandwidth.

The Phase Shifter Element

The photograph of an experimental model is shown in Figure 3. Conductivity modulation was performed along a vertical strip, as can be seen from the bias line configuration, rather than thruout the entire slab. This geometry makes more efficient use of injected carriers, placing them in the region of maximum RF electric field.

The absolute equivalent circuit is shown in Figure 4. The waveguide impedance definition, Z_n, and the reactance, jX, appropriate to this obstacle are based upon the RF current magnitude carried by the strip with the control gaps shorted.[2] The lumped impedance parameters (R_F, R_R and jX_C) in series with the strip can be determined either by calculation (from the dimensions, material resistivity and dielectric constants) or by slotted line measurements.

Arbitrarily, a 12 gap control structure was chosen. The gap width was 3 mils and this resulted in a net series capacitance of 0.03 pf., or $-jX_C = -j2$ kilohms at 3 ghz. This is noteworthy, since PIN switching diodes typically have 10-100 times as much capacitance but less than 1/10th the volume of the active region of this bulk element. So far the best conductivity modulation has resulted in $R_F = 35$ ohms (with a 2 ampere bias). This corresponds to an effective resistivity of the silicon in the control gap region of 1 ohm-cm, However, the resistance with zero bias was only 0.3 kilohms. This corresponds to about 10 ohm-cm resistivity, far less than would be expected with the 2 kilohm-cm starting material. It seems likely this low value of resistance was caused by surface contamination which occurred in the fabrication of these phase shifter elements.

A phase shifter element with these parameters would yield about 12° of phase shift per db of loss at 3 ghz. This is about 1/17 of that already achieved by the conventional PIN diode phase shifter[1]. Therefore, it is certainly necessary to raise the effective resistivity in the vicinity of the control gaps. With better fabrication procedure and the use of reverse bias (not used here because of the high surface leakage current path) it seems reasonable to suppose that this resistivity could be increased to 1 kilohm-cm. Some of the attendant reduction in reverse biased loss could then be exchanged for reduced loss under forward bias (by using fewer gaps and/or a higher value of Z_n) to equalize the loss incurred in the two states. Given this improvement, over 150° of phase shift per db of loss could be obtained; and the bulk element would have an insertion loss competitive with the conventional PIN diode.

However, the feasibility of microwave control by bulk semiconductor devices with its associated reduction in RF capacitance thru the use of orthogonal bias and RF terminals already is demonstrated. Moreover the large physical size of these elements can be expected to produce greatly increased RF power handling capability.

Acknowledgement

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References

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2. J. F. White and C. S. Ward, "A 60 Kw diode phase shifter with predictable performance at C-band in rectangular waveguide," Int. Solid-State Circuits Conf, 1968, See pp. 8-9 of technical paper digest.

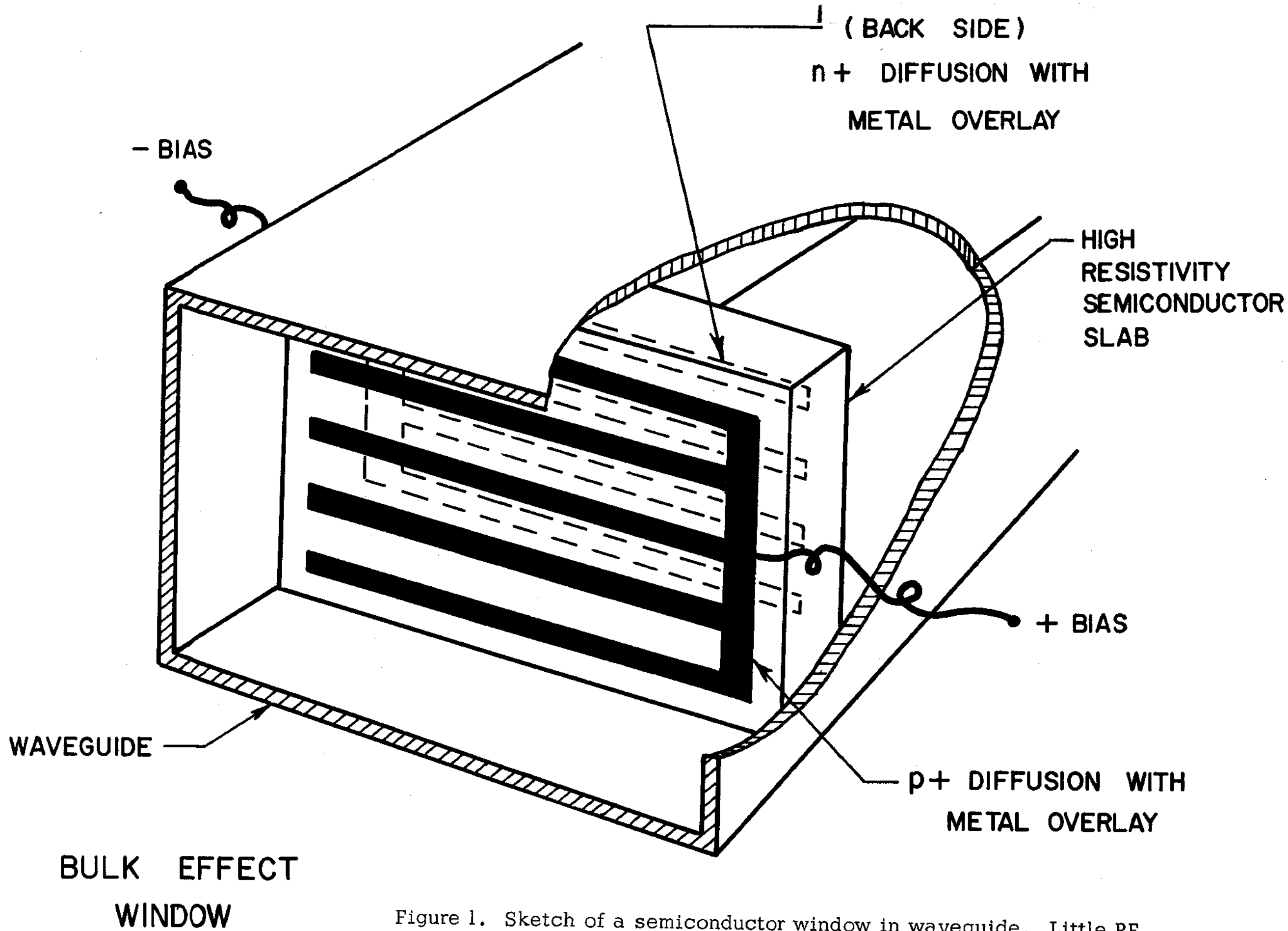

Figure 1. Sketch of a semiconductor window in waveguide. Little RF reflection results from the injecting structures if the metal lines are thin compared with the wavelength of operation.

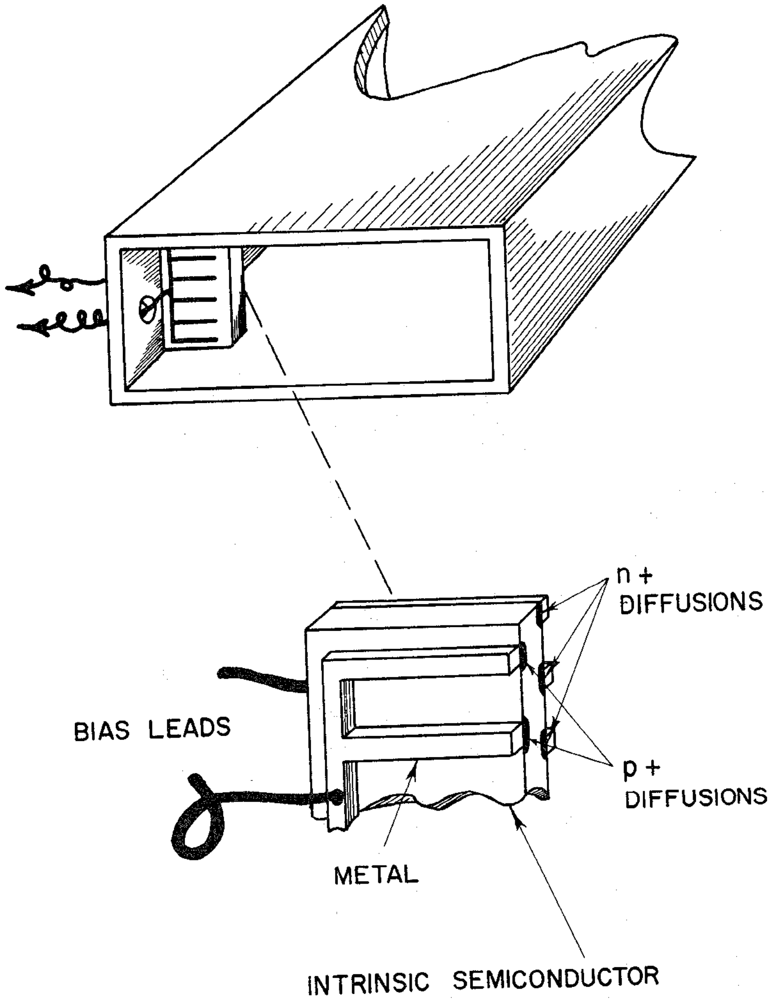

Fig. 2. Plan view of a switchable inductive susceptance in waveguide, implemented with the bulk semiconductor switching method.

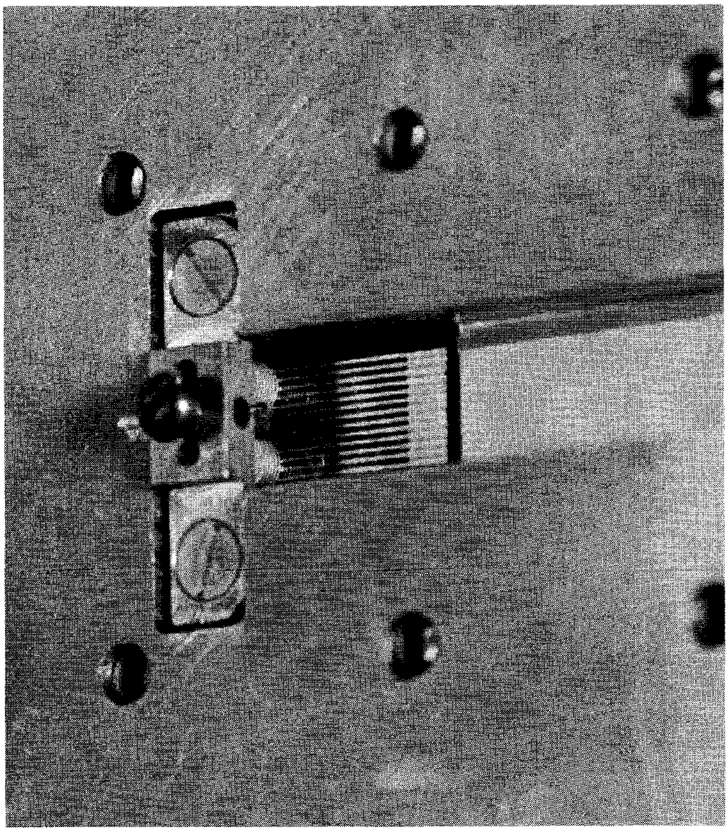

Figure 3. Photograph of an S-band phase shifter element. Light areas show gold plate over a boron diffusion. Dark regions are the oxide layer, residual after the planar fabrication process.

Fig. 4. Dimensions and equivalent circuit for the S-band bulk phase shifter element
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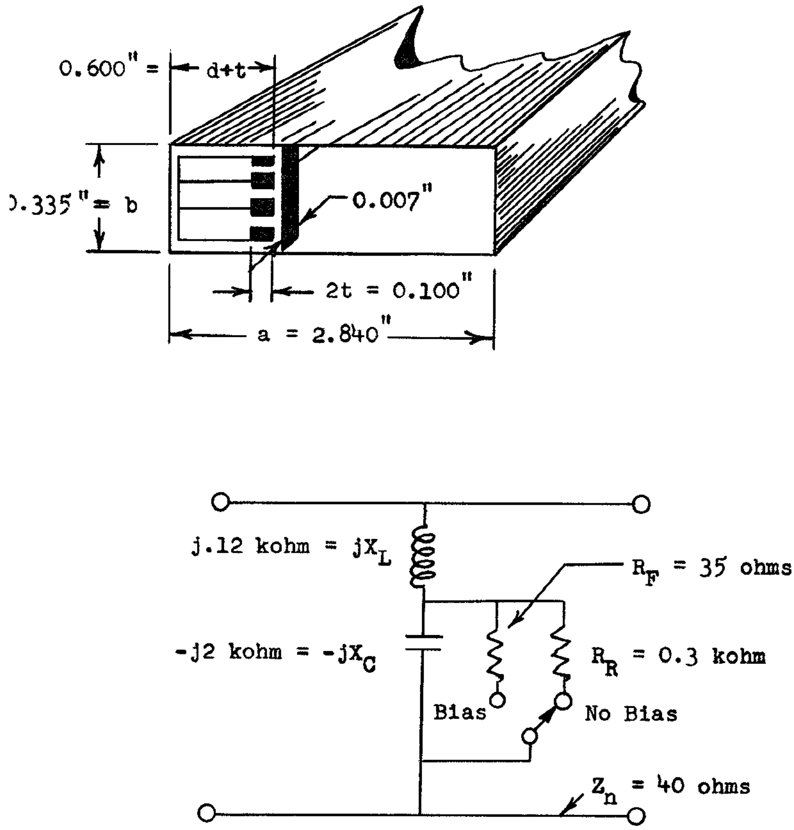

$$Z_n = 2\sqrt{\frac{\mu_o}{\epsilon_o}} \cdot \frac{\lambda_g}{\lambda_a} \cdot \frac{b}{a} \cdot \sin^2(\pi d/a)$$