# Microstrip Transmission on Semiconductor Dielectrics

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*Abstract*—As a result of both a larger number of microwave functions performed by semiconductor devices and a larger number of functions required in modern systems, it has become highly desirable from both the system and the device standpoint to fabricate multiple microwave semiconductor devices on a common substrate. The use of multiple devices in a single package has system and reliability advantages, but there is also offered the possibility of improved performance of the microwave components. This results from the elimination of packaging of each individual element and the ability to place the package interface in a more advantageous position in the circuit.

To effect such an improvement, an efficient means of microwave interconnection must be available. The interconnections must have not only low dissipative losses through the microwave region, but be capable of providing the impedances necessary for transformations by the various microwave functions and for circuit resonating elements. The range of impedance commonly required is of the order of 20 Ω to 80 Ω.

To be compatible with semiconductor materials and processing, the choice of dielectric material was limited to film dielectrics, possibly $SiO_2$, or the use of the semiconductor material itself as a dielectric. For both semi-insulating gallium arsenide and silicon of resistivity greater than 1000 Ω-cm, the loss is sufficiently low to perform efficient interconnection of devices on a common substrate and is considered even suitable for other components such as directional couplers and hybrids where extremely high $Q$ is not required.

## Introduction

THE INCREASING number of microwave functions that can be performed by semiconductor devices has contributed to the growth of systems, such as phased array radar, that require a multiplicity of repetitive microwave functions. Their repetitive nature is, in certain respects, similar to the repetitive characteristics of digital computer circuitry. Thin film and monolithic circuits that have made low cost digital logic possible should also be applicable to the fabrication of microwave function groups.

Many of the components found in modern low-frequency integrated or thin film circuits such as resistors, capacitors, and transistors, are also required in integrated functions. But, in addition, there must be available transmission-line components such as couplers, filters, and transforming sections. These must be fabricated from transmission line sections having low-loss and well-defined characteristic impedance properties using processes and materials compatible with the other circuitry components.

The loss characteristics, to a large extent, determine the areas of possible usage. For interconnecting two circuits operating at 50-Ω characteristic impedance and located adjacent to each other, a line loss of 3 to 5 dB per cm or higher is acceptable. In the design of filters and couplers, the length of transmission line required is a function of the desired operating frequency; therefore, the important factor is loss per wavelength. Directional couplers and 3 dB hybrids can be fabricated having satisfactory characteristics with as much as 0.5 to 1.0 dB loss per wavelength. Band-pass filter structures generally require lower loss transmission-line characteristics, usually in the region of a few hundredths of a dB per wavelength for steep skirt response and low insertion loss.

The necessary transmission line impedances are dictated both by the need to operate with circuitry other than that in integrated form and the need to provide transformation and coupling to various semiconductor devices. A 50-Ω transmission line impedance is used almost universally for coaxial and strip-line transmission in present day equipment. Also, the measuring equipment such as signal generators, wave meters, and slotted lines all operate at a 50-Ω characteristic impedance. Present microwave semiconductor devices require impedances both higher and lower than 50 Ω. The input impedance of most transistor and varactor devices is generally below 50 Ω, while the impedance of most mixer diodes and the output impedance of transistors, is above 50 Ω. Switching diodes and tunnel diodes operate with transmission lines of approximately 50-Ω characteristic impedance. An impedance range from 20 to 100 Ω should be considered adequate for a large majority of microwave circuit applications.

To produce a transmission line compatible with the materials, processing, and techniques currently used to produce the devices, the choice of dielectric material for the transmission line was limited to film dielectrics, possibly $SiO_2$, or the use of the semiconductor material itself as a dielectric. For the range of impedances required, the use of the semiconductor material itself offers more reasonable line widths and is apparently a satisfactory approach to microwave interconnection and monolithic systems.

A choice of dielectric material imposes limitations not only on processing techniques and materials, but also on certain geometries as well. For a silicon dielectric material, for instance, only planar transmission-line configurations can be considered. The double ground plane or triplate transmission line has found wide acceptance, but for use with silicon the high relative dielectric constant (11.7) restricts the characteristic impedance that can be achieved with triplate construc-

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tion and practical silicon thicknesses to something less than 50 Ω. The use of single ground plane transmission line (microstrip transmission line) offers not only simpler construction but, as will be shown later, characteristic impedances covering the full range required by semiconductor circuits. The characteristic of microstrip transmission line on semiconductor dielectric material will be discussed in the following sections.

## Theoretical Studies of Microstrip Transmission

Planar transmission lines with single ground planes gained prominence in 1952 with the publication of papers on applications and a simplified theory of transmission by Assadourian and Rimai [1]. This solution was approximate in both determination of field distribution and line capacitance, and in the assumption of TEM propagation. Another more rigorous determination of the parameters of microstrip line was made by Black and Higgins [2], but unfortunately their solution was good only for the case of infinite and uniform dielectric media. This condition would, in general, exist only with air insulated microstrip transmission line.

Investigators of microstrip transmission line had realized, of course, that a TEM solution could only approximate the actual transmission mode. In still later work, Wu [3] outlined a procedure for an exact solution of the microstrip transmission case. However, due to the complexity of the solution, general curves and design charts for microstrip transmission were not considered feasible.

Lacking a rigorous, practical solution, the insertion loss and characteristic impedance properties of microstrip transmission lines were determined experimentally. Calculations of loss and characteristic impedance as predicted by the TEM solutions are presented for comparison only.

## Experimental Determination of Microstrip Characteristics

The major portion of the investigation was devoted to the use of silicon as the dielectric material. This was due both to the large number of discrete microwave devices (varactors, transistors, mixer diodes, etc.) in silicon and to the availability of the necessary materials and technology. Slices of both $P$- and $N$-type silicon of various resistivities were polished to 0.010-inch ±0.005-inch thickness, leaving an optical quality surface suitable for evaporation and processing. One side of each slice was completely metallized to serve as a ground plane and, on the opposite side, lines of various widths from 1 mil to 20 mils were produced. Both aluminum and silver were investigated as conductors.

To provide a low VSWR transition from coaxial line to microstrip with an 0.010-inch thick dielectric, it was necessary to reduce the size of the coaxial line to dimensions comparable to that of the microstrip line. A linear transformation was made from 0.141-inch coaxial components down to a coaxial section having 0.050-inch outside diameter and 0.015-inch inside diameter. Teflon insulation was used through this small section of line. This test fixture is shown in Fig. 1. The VSWR of the two transforming sections in cascade remained below 1.1 from 8 to 12 Gc/s and the combined insertion loss of both transforming sections increased from 0.2 dB to 0.3 dB in the same frequency range. The length of the transmission line under evaluation was 0.625 inch.

The measured insertion loss of matched transmission line as a function of silicon resistivity is shown in Fig. 2. Resistivities used were of the order of 100 Ω-cm, 300 Ω-cm, 800 Ω-cm, and 1300 Ω-cm. The range and accuracy of the resistivity measurements are indicated by the length of the rectangle representing the measured points and the range and accuracy of the insertion loss measurements are presented by the height of the rectangles.

The resistivity and dielectric constant of silicon have recently been shown to be unchanged at microwave frequencies from the commonly quoted low-frequency values [4], [5]. The dissipation factor $D$ can be computed from these values by:

$$D = \frac{1}{\omega RC} \cdot$$

Considering $R=\rho(t/A)$ and $C=\epsilon(A/t)$ this expression reduces to:

$$D = \frac{1}{\omega\rho\epsilon} \cdot$$

This formula applies only to those materials having losses due solely to migration of charge carriers. In ordinary dielectric material, the bulk resistivity is extremely high, and the dissipation factor stems from energy consuming processes not related to ohmic losses. All measurements to date on silicon have shown only ohmic losses, indicating very low losses of the frequency invariant type that are common to dielectric materials.

With dielectric materials having only ohmic losses, the dissipation factor is inversely proportional to frequency and, therefore, the line loss due to dielectric dissipation will be constant per unit length. This compares to a line loss proportional to frequency for ordinary dielectric materials. As a result, the loss per wavelength using silicon dielectric will decrease with increasing frequency.

The loss tangent and dielectric losses of microstrip transmission line as well as the conductor losses can be computed as outlined by Assadourian and Rimai [1]. This curve is shown in Fig. 2 for comparison with the experimental values. In all instances, the measured insertion loss is less than predicted by the approximate theory. Dukes [6], among other authors, has noted that the losses predicted by Assadourian and Rimai are higher than those actually observed.

The insertion loss as a function of conductor thickness was also determined. Silicon slices of resistivities of

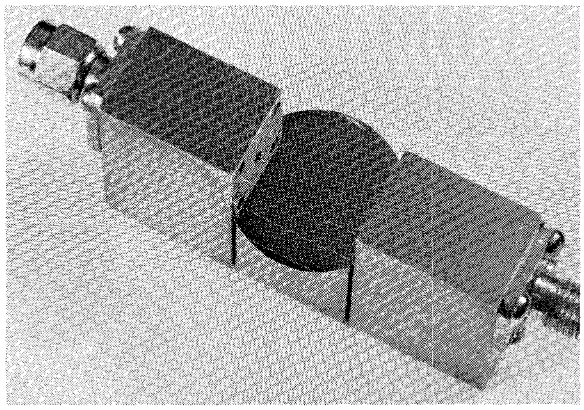

Fig. 1. Photo of text fixture for measuring microstrip transmission lines.

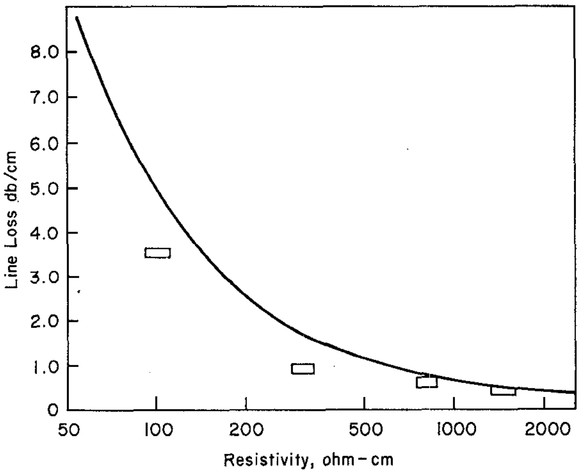


Fig. 2. Microstrip line loss as a function of dielectric resistivity.

1400–1600 Ω-cm range were prepared with aluminum conductors as previously described. Conductor thicknesses from 10 to 400 microinches were tested, and the insertion loss as a function of line thickness is presented in Fig. 3. This curve parallels closely that which could be computed on the basis of microwave resistance of the conductor with the 35-microinch skin depth in aluminum at this frequency.

Microstrip transmission lines using high resistivity silicon as the dielectric material can have losses at room temperature approaching that of the conductors alone. However, as the temperature increases, charge carriers are thermally excited, lowering the resistivity of the material. As the temperature is lowered, the resistivity of the material is again reduced due, in this case, to the increase in mobility of the charge carriers with decreasing temperature. Due to the lower resistivity at both hot and cold temperatures and the resulting increase in insertion loss at these extremes, a curve of strip-line loss as a function of temperature was produced. This curve is shown in Fig. 4. With the sample tested, the loss stays between 0.45 and 0.50 dB/cm from 5°C to +110°C.

The variation of resistivity with temperature for lightly doped silicon has recently been computed by Runyan [7] and is presented here as Fig. 5. The results

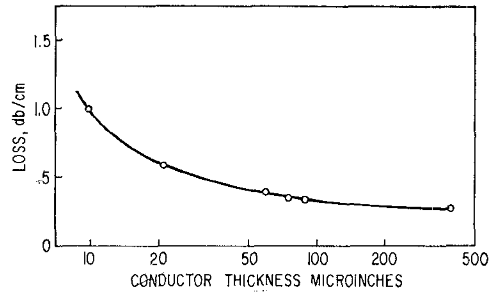


Fig. 3. Microstrip line loss as a function of conductor thickness.

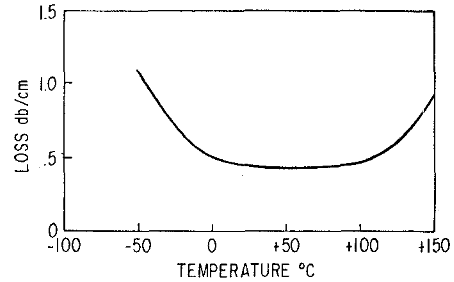


Fig. 4. Microstrip line loss on 1500-Ω silicon substrate.

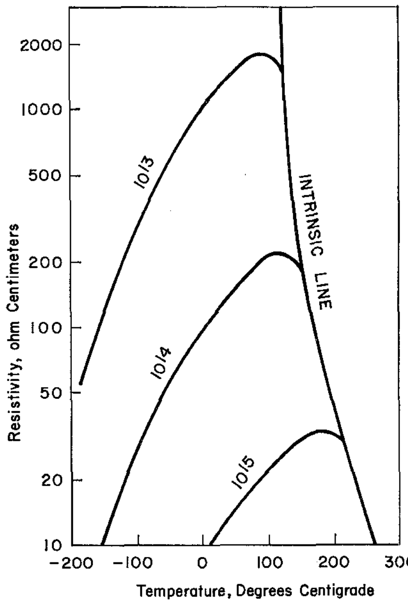


Fig. 5. Silicon resistivity vs. temperature and impurity concentration (boron doped type).

of the microstrip loss measurements correlated perfectly with the predicted resistivity vs. temperature for $P$-type silicon having an impurity concentration of approximately $10^{13}$ atoms/cc. Although little, if any, improvement in high temperature operation can be expected, it is possible to compensate the material to maintain high resistivities at lower temperatures to provide operation across the usual military operating temperature range.

The characteristic impedance of the microstrip lines was determined as a function of line width by slotted line impedance measurements. As only a limited length of transmission line was available and unknown discontinuities were present at each transition, the tech-

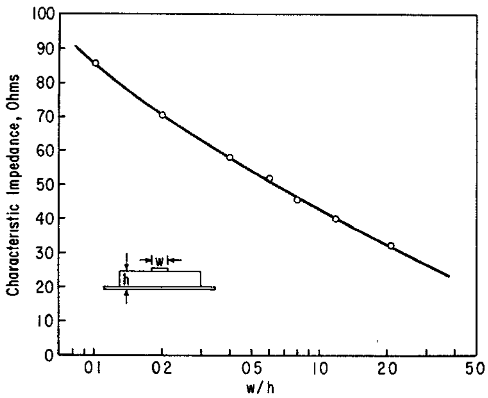


Fig. 6. Measured impedance of microstrip line on silicon dielectric.

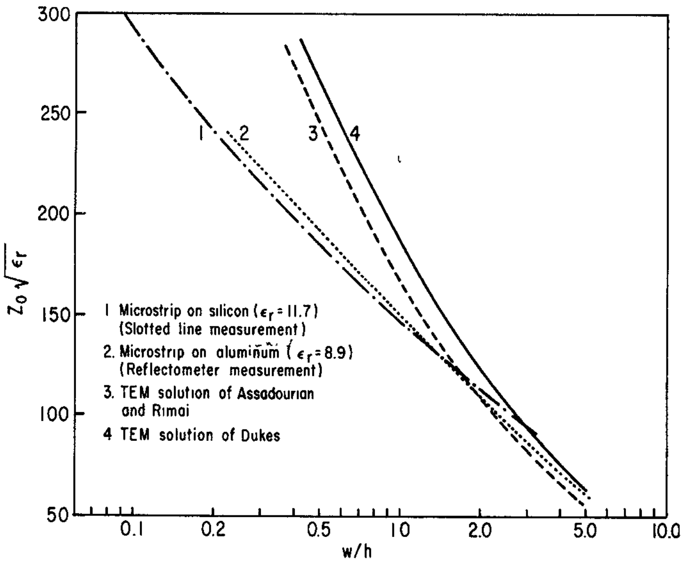


Fig. 7. Comparison of measurements with theoretical solutions of microstrip transmission lines.

niques by which characteristic impedance could be determined were limited. The method chosen was based on that described by Arditi [8]. Instead of physically modifying the transmission line, the electrical length was changed by changing the frequency. A technique similar to this has been reported by Lenzing [9].

Through slotted line measurements, the characteristic impedance of lines ranging in width from 1 mil to 20 mils on a 10 mil thick silicon substrate was determined. The results are shown in Fig. 6. This impedance curve was normalized for comparison with other solutions by multiplying the characteristic impedance by the square root of the dielectric constant and by expressing the line width as width divided by dielectric thickness, or $w/h$ ratio. The measured results so normalized are shown as Curve 1 in Fig. 7. The impedance as a function of $w/h$ from the solution of Assadourian and Rimai is given as Curve 3, and the solution of Dukes based upon electrolytic tank measurements is given as Curve 4. There is relatively good correlation between the solution of Assadourian and Rimai and the solution of Dukes and, for values of $w/h$ greater than 2 there is close agreement with the measurements on the silicon dielectric. For values of $w/h$ less than 1, however, there is considerable disagreement in characteristic impedance. As a verification of the silicon measurements, microstrip transmission lines were deposited on a 2-inch square 0.030-inch thick aluminum oxide (96 percent purity) slice. The characteristic impedance of these lines was measured using both slotted line impedance plots and a time domain reflectometer. The results of these measurements are shown as Curve 2 of Fig. 7.

The results obtained on a aluminum oxide substrate using different techniques of impedance measurement substantiate the measurements on the silicon dielectric lines. The deviation from the theoretically predicted Curves 3 and 4 is without doubt due to the approximate nature of the solution.

## Conclusion

The transmission line techniques described in the preceding sections provide a means not only for high quality interconnection between microwave functions, but for the fabrication of transmission-line devices such as couplers, hybrids, and even simple filter structures where extremely high $Q$ is not required. High resistivity semiconductor grade silicon has much to offer as a dielectric material. It is by far the purest and most uniform material ever used as a microwave dielectric. Problems associated with dielectric constant variation from sample to sample are not present with silicon. The surface is capable of being polished to any desired finish to serve as a base for a wide variety of thin film components. For large microwave hybrid structures, as found from UHF through $L$-band, ceramic and printed circuit techniques appear most desirable. At higher frequencies, the use of a silicon monolithic construction offers many fabrication and reliability advantages and, in most applications, it should be economically competitive with other techniques.

Microstrip transmission is far from new, but the use of this transmission technique with integrally formed semiconductor devices provides the opportunity for simpler, less expensive microwave components of improved performance. One of the earliest such circuits is shown in Fig. 8. This is the contract pattern for an $X$-band mixer monolithic circuit. It consists of a branch type 3-dB hybrid followed by one-quarter wavelength matching transformer sections to the diode locations. Two top contact Schottky barrier diodes will be formed in the silicon before metallization. A one-quarter wavelength open-circuit stub provides filtering for the output. The overall size of the entire circuit is 0.160 by 0.260 inch.

There are other semiconductor materials that have the characteristic necessary for low-loss microwave propagation. Semi-insulating gallium arsenide, for instance, with a resistivity greater than $10^8$ Ω-cm was evaluated as a microstrip dielectric material in a manner similar to that described for silicon. Measured losses were slightly lower than those observed for silicon and, in fact, approached very closely the losses inherent

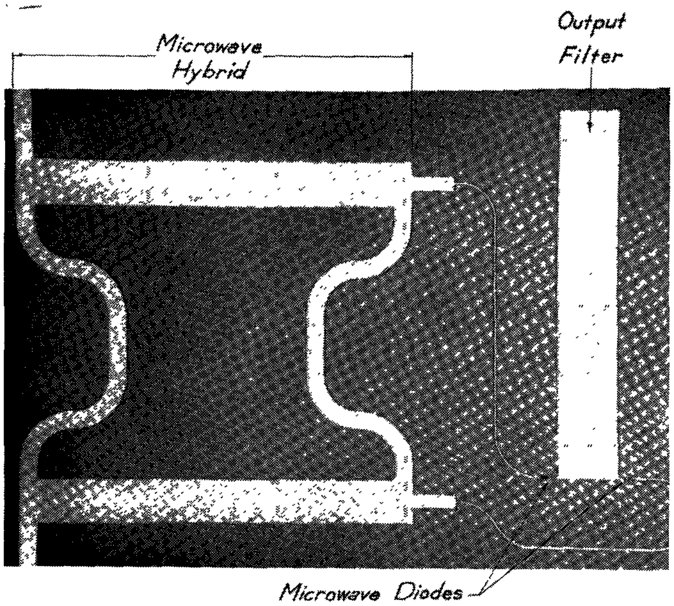


Fig. 8. Contact pattern for balanced mixer integrated circuit.

in the conductors. As nearly all microwave semiconductor devices in operation today are of either silicon or gallium arsenide, the ability to interconnect these devices and perform transmission-line functions in an efficient manner should enable many system advances heretofore limited due to size, cost, or weight of the microwave components.

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# A Digital Latching Ferrite Strip Transmission Line Phase Shifter

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***Abstract*—This paper is concerned with the development of a new type of latching phase shifter which combines submicrosecond switching with a compact strip transmission line structure. Digital increments of nonreciprocal phase shift are obtained by "latching" or switching the magnetization of appropriate square loop garnet or ferrite materials from one remanent state to another. The following data have been obtained for a four-bit, *C*-band model utilizing yttrium iron garnet ($4\pi M_s = 1600$ G):**

**Center Frequency—5.45 Gc/s**
**Phase Deviation—$\leq \pm 3$ percent over an 8 percent frequency band**
**Insertion Loss—$<0.9$ dB**
**VSWR—$<1.50$**
**Switching Time—$<0.3\mu$s with a 130 V, 13 amp pulse**
**Switching Energy—$<200$ $\mu$J for 180° bit**
**Length—$<6$ inches.**

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## INTRODUCTION

RECENT EFFORT has been extended toward the development of digital latching waveguide phase shifters and the associated driver circuitry [1]–[4]. This paper is concerned with the development of a somewhat different type of phase shifter which utilizes the properties of square loop magnetic toroids placed in a strip transmission line geometry.

Before the development of the new phase shifter is described, the basic principles involved need to be reviewed. This will be accomplished by considering, first, the nature of present waveguide latching ferrite shifters. A discussion of the evolution of nonreciprocal TEM mode components follows; finally, the present effort is described.