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Slow-Wave Coplanar Strip Lines on Semiconducting Substrates

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Abstract

A new type of coplanar strip line on semiconducting substrates, which supports low-loss propagation of a slow quasi-TEM wave at microwave frequencies, is described. The new line is potentially highly useful for monolithic integration of microwave semiconductor devices and also for construction of a new class of distributed functional devices. Propagation modes, design considerations and formulas for fundamental transmission characteristics are presented together with a confirmation of the mode existence by a preliminary experiment carried out on a line piece formed a GaAs substrate.

1. Introduction

The standard form of integrated circuits at microwave frequencies (MIC ; microwave integrated circuits) is at present of the hybrid type, where active semiconductor devices and passive lumped or distributed circuit elements are combined on high-quality dielectric substrates, which also serve as the principal propagation media for the electromagnetic waves travelling along a microstrip or coplanar waveguide.

Obviously, such a form of integration makes a distinct contrast to those of more conventional digital and analog semiconductor integrated circuits at lower frequencies, where the so-called "monolithic" approach is employed to its fullest extent, resulting in low-cost and high-yield batch fabrication processes with simultaneous achievement of high reliabilities of devices and circuits. In comparison to the monolithic approach, the hybrid approach at microwave frequencies requires an increased number of more sophisticated fabrication steps, which inevitally leads to higher cost, lower yield, smaller scale of integration and reduced reliability.

The principal reasons why the monolithic approach breaks down and the hybrid approach becomes more suitable at microwave frequencies appear to be as follows : (1) The quasi-TEM waves propagating through semiconducting substrates along planar metal strips suffer considerable loss at microwave frequencies, in particular when the substrate resistivity is low[1]. (2) When distributed-parameter circuits such as transmission-line filters, resonators and couplers are constructed on semiconducting substrates, their sizes, which are primarily determined by the wavelengths of the electromagnetic waves, tend to be still too large to match those of semiconductor active devices, resulting in inefficient and uneconomical use of

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expensive semiconductor materials, and also in the difficulties in mask pattern designs owing to the increased range of dimensions involved in patterns. (3) The conventional technique of device isolation by reverse-biased $p-n$ junctions becomes less useful due to high junction capacitances which provide very low impedances and poor isolation at microwave frequencies.

The purpose of the present report is to describe a new class of strip waveguides on semiconducting substrates which will possibly overcome the above mentioned difficulties and will enable one to achieve, with the use of the conventional semiconductor integrated circuit technology, firstly a complete monolithic integration of active and passive microwave semiconductor devices, and secondly construction of new types of semiconductor distributed-parameter devices based on non-linear properties of the slow-wave mode.

One basic structure of the new strip waveguides is shown in Fig. 1, and it is a coplanar strip line formed on an oxide-semiconductor double-layer substrate. Owing to the semiconducting property of the substrate, a slow quasi-TEM mode propagates along such a line with a linear dispersion and small attenuation. Another important feature of the new line is that the line properties can be made variable, if the bias-dependent non-linearity of the semiconductor depletion layer is fully utilized. This provides electronic tunability and various parametric effects to the line which will be beneficially made use of for the construction of a new class of functional devices. As for the semiconducting materials of the new line, either silicon SOS technology or compound-semiconductor technology as shown in Fig. 1 for the case of GaAs, can be applied, and in the latter case, the line structure is particularly suitable for the integration of the microwave circuits containing GaAs MESFET's.

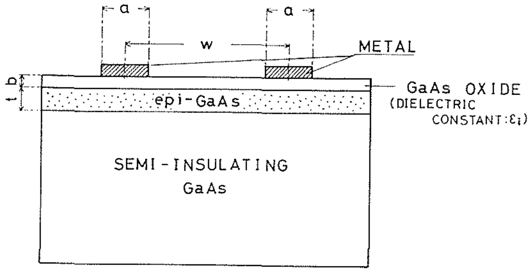

Fig. 1 A Balanced Coplanar Strip Line on Semiconductor Substrate (MIS-type)

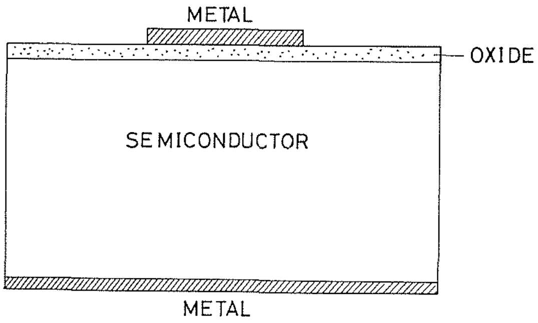

Fig. 2 A Microstrip Line on Oxide-Semiconductor Duble-Layer

The fundamental physical principle of the new coplanar line is similar to that of the microstrip line formed on the oxide-semiconductor double-layer system shown in Fig. 2. The transmission properties of this type of microstrip line were originally studied by Guckel et al[2)], and by Hasegawa et al[3)~5)]. Extension of analysis on such a microstrip line to incorporate the non-linearity of the semiconductor depletion layer capacitance in the form of either MIS structure or Schottky contact has been, until recently, the subjects of various authors[6)~12)]. However, in the case of the microstrip configuration, the upper cut-off frequency of the slow-wave mode is several GHz at the highest, and beyond this frequency, the slow-wave mode suffers a serious propagation loss. This fact imposes a severe limitation on the possible applications of the microstrip line. On the other hand, the slow-wave cut-off frequency of the present coplanar strip line can be made much higher than that of the microstrip line by the reduction of the skin-effect loss. Additionally, an increase of the slowing factor λ_0/λ_g (λ_0: free space wavelength, λ_g: guide wavelength) is possible, and also the structure is more suitable to the planar integration of various devices.

The propagation modes, design considerations and the fundamental transmission properties (characteristic impedance and slowing factor) are presented in this report together with some preliminary experimental results using GaAs coplanar lines, which supports the validity of the basic concepts.

2. Propagation Modes

The basic coplanar line structure shown in Fig. 1 is of balanced type. However, it can be readily modified into a more conventional form of coplanar waveguide of unbalanced[13)]. Another feature of the basic structure in Fig. 1 is that it is of *MIS* (metal-insulator-semiconductor) type, but it can be modified into Schottky type by removing the oxide layer and forming Schottky contacts directly on the surface of the semiconducting layer. From a material point of view, the line can be alternatively constructed with the use of the silicon SOS technology, as already mentioned earlier. Although only the basic structure in Fig. 1 is considered in what follows, the above modifications and a considerable amount of other modifications and sophistications are possible, and their transmission properties may be discussed as extensions of the present analysis of the basic structure.

However, even the simplest basic line structure shown in Fig. 1 involves a lossy medium separated by complicated boundaries, and an exact analysis of the wave propagation starting from the Maxwell's field equations appears extremely difficult. A more practical approach is therefore employed here, which is a quasi-static approach based on the following physical considerations.

Ignoring the loss due to the non-zero conductivity of the semi-insulating GaAs whose d. c. resistivity is typically of the order of 10^8 ohm-cm, one would easily recognize the presence of the following two limits of wave propagation along the basic structure in Fig. 1:

(1) When the conductivity of the thin semiconducting GaAs layer is high enough to prevent the penetration of both electric and mangetic field lines, the semiconducting layer will act as a metallic wall.

(2) When, on the other hand, the resistivity of the semiconducting layer is high enough to allow the penetration of both electric and magnetic field lines, the semiconducting layer will act as a dielectric layer. For these two limits, the fundamental propagation modes are obviously usual quasi-TEM modes whose propagation velocity is primarily determined by the permittivity values of the media.

Between the above metallic and dielectric limits, however, there exists yet another limit, i. e., the following "semiconducting" limit:

(3) When the conductivity of the semiconducting layer is intermediate and the frequency is low, the semiconductor layer will prevent the penetration of electric field lines, but will allow the penetration of magnetic field lines.

The third limit of the above implies that the electric energy and the magnetic energy are stored in spacially different places in such a situation, making the product LC of the effective inductance L and the effective capacitance C per unit length of the line, become much larger than the product of the permittivity and permeability of the loading medium. In other words, the propagation velocity given by $v=1/\sqrt{LC}$ can become very small, although the field distribution is still almost transverse-electromagnetic (TEM). This quasi-TEM slow-wave mode is the most interesting fundamental mode of the basic line structure owing to its slow-wave nature.

The amount of attenuation suffered by such a slow-wave mode can be related in the first approximation to the increasing imperfectness in both of electrical polarization and magnetic polarization during exchange of energies, as the frequency is increased. That is to say, as the frequency is increased, a part of the electric energy is lost by the relaxation of electrical interfacial polarization, and at the same time, a part of the magnetic energy is also lost by the increased skin-effect, or in other words, by the increased longitudinal current through the semiconducting layer causing conduction loss. The latter skin-effect loss may also be described as a kind of relaxation of magnetic polarization.

On the basis of the above physical consideration, an equivalent circuit of the slow-wave mode could be drawn as shown in Fig. 3. With reference to Fig. 3, one can define the electrical relaxation frequency f_ε and the magnetic relaxation frequency f_δ through

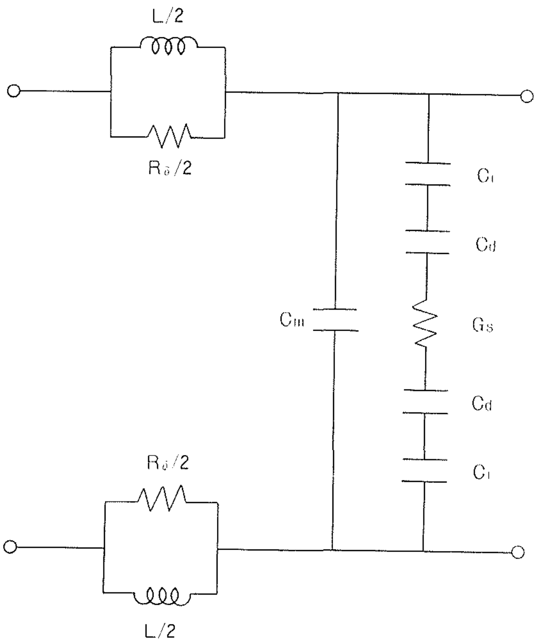

Fig. 3 An Equivalent Circuit Representation of Slow-wave Mode

$$f_\varepsilon=\frac{1}{2\pi}\frac{G_s}{(C_{id}/2)}\frac{C}{(C_{id}/2)} \tag{1}$$

$$f_\delta=\frac{1}{2\pi}\frac{R_\delta}{L} \tag{2}$$

where

$$C_{id}=\frac{C_iC_d}{C_i+C_d} \tag{3}$$

and

$$C=\frac{C_{id}}{2}+C_m \tag{4}$$

$=$ total line capacitance.

The upper cut-off frequency f_0 of the slow-wave mode is then given by

$$f_0=[f_\varepsilon^{-1}+f_\delta^{-1}]^{-1} \tag{5}$$

From the equivalent circuit Fig. 3, the characteristic impedance Z_0, the slowing factor λ_0/λ_g and the attenuation constant α are calculated in the first approximation as follows:

$$Re(Z_0)=\sqrt{\frac{L}{C}} \tag{6}$$

$$Im(Z_0)=\frac{1}{2}\sqrt{\frac{L}{C}}[(f/f_\varepsilon)-(f/f_\delta)] \tag{7}$$

$$\lambda_0/\lambda_g=\sqrt{\left(\frac{C}{\varepsilon_0}\right)\left(\frac{L}{\mu_0}\right)} \tag{8}$$

$$\alpha=\frac{\pi\sqrt{LC}}{f_0}f^2 \qquad /9/$$

The attenuation per wavelength is obtained as

$$\alpha\lambda_g=\pi(f/f_0) \tag{10}$$

3. Design Considerations and Fundamental Transmission Properties

In order to overcome the difficulties for monolithic integration of microwave semiconductor devices, the waveguide structure should provide (1) a small propagation loss, (2) a large slowing factor, or reduced wavelengths, and (3) compatibility with a suitable device isolation technique. In the present coplanar line, the requirement (3) can be readily satisfied with the use of the mesa-etching technique or the dielectric isolation technique by oxidation, since the bulk of the substrate is already semi-insulating or truly insulating (in the case of SOS technology). On the other hand, to fulfill the requirements (1) and (2) of the above, the line parameters should be carefully determined to optimize the characteristics of the line.

As compared with the microstrip line of the type of Fig. 2, the present coplanar line has a remarkable feature in that the thickness of the semiconducting layer can be made small, thereby reducing the skin-effect loss to a considerable extent. In other words, the situation of $f_\delta \gg f_\varepsilon$ can be easily realized by making the thickness t of the semiconducting layer much smaller than the skin-depth $\delta=\sqrt{2/(\omega\mu_0\sigma_s)}$ where σ_s is the conductivity of the semiconducting layer. Under such a condition, the upper cut-off frequency of the slow-wave mode is approximately given by

$$f_0\simeq f_\varepsilon\simeq\frac{\sigma_s}{\pi\varepsilon_0\varepsilon_i}\left(\frac{t}{W}\right)\left(\frac{b}{a}\right) \tag{11}$$

With a proper choice of line parameters, f_0 given by Equation (11) can be higher than 100 GHz. On the other hand, the value of f_0 in the microstrip case is several GHz at the highest, being severely limited by the skin-effect in the semiconducting layer whose thickness cannot practically be made smaller than 50 μm. Thus, the new coplanar line is potentially much more useful.

The slowing factor λ_0/λ_g and the characteristic impedance are determined by the line inductance L and the line capacitance C as given in Equation (6)-(8). In Fig. 4, $Re(Z_0)$ and λ_0/λ_g are plotted on L-C plane, and this type of figure is useful for the purpose of the line design.

On the basis of the quasi-static consideration in the previous section, the line inductance L can be analytically obtained by the standard conformal mapping technique[14], ignoring the presence of the semiconducting layer. The result is

$$L=\mu_0\frac{K(k')}{K(k)} \tag{12}$$

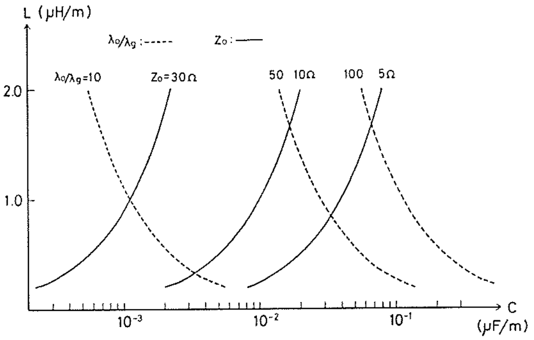

Fig. 4 Curves for Slowing Factor λ_0/λ_g and $Re(Z_0)$ on L-C Plane

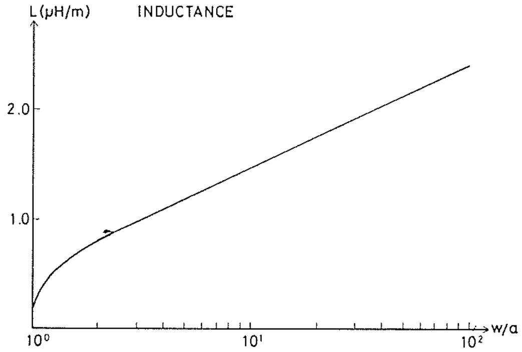

Fig. 5 Calculated Line Inductance vs. w/a

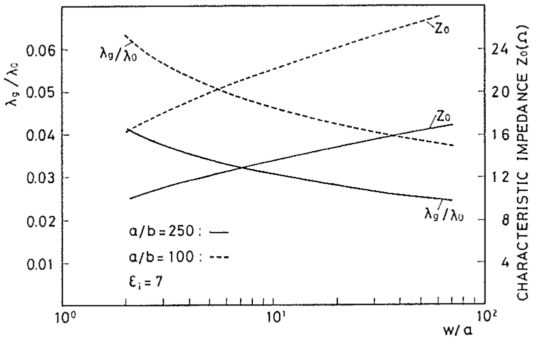

Fig. 6 Calculated Values of Slowing Factor and $Re(Z_0)$ vs. w/a

where

$$K(\alpha)=\int_0^{\pi/2}\frac{d\theta}{\sqrt{1-\alpha^2\sin^2\theta}}$$
$$k'=\sqrt{1-k^2}=\frac{w-a}{w+a} \tag{13}$$

Fig. 5 shows the computed values of the line inductance L vs. w/a.

On the other hand, the evaluation of the line capacitance is much more difficult owing to the complicated dielectric boundaries and the presence of the semiconductor depletion layer. However, for most practical applications where the condition of $b \ll w, a$ holds, one could approximately use the following formula for the ideal MIS system, assuming $C_m=0$.

$$C_i=\frac{\varepsilon_0\varepsilon_i a}{b}, \quad C_d=\frac{\varepsilon_0\varepsilon_s a}{W_d} \tag{14}$$

where ε_s is the permittivity of the semiconducting layer and W_d is the width of the semiconductor depletion layer which is a function of the *d. c.* bias as is given in standard textbooks on semiconductor devices[15].

In order to give a rough idea on the values of transmission parameters obtainable with the present coplanar line, curves of $Re(Z_0)$ and λ_g/λ_0 calculated using Equations (12) and (14) are given in Fig. 6 for the case of $C_d=\infty$.

4. Experimental Results

In order to confirm the propagation of the slow-wave mode along the present line structure, a preliminary experiment was performed on a line sample fabricated on $Cr-0$ doped semi-insulating GaAs substrate. The sample was fabricated as follows: An epitaxial n-type GaAs layer with a carrier concentration of $6 \times 10^{15}\,\mathrm{cm}^{-3}$ and the thickness $t=20\,\mu\mathrm{m}$ was grown on the substrate by the standard LPE technique. The resistivity of the layer was 0.25 ohm-cm. Then, the top of the epi-layer was anodically oxidized using the process of Hasegawa et al[16], and an oxide layer with a thickness of 4000 Å and the specific permittivity of about 7 was formed. Finally, gold metal strips were formed on the oxide layer with the standard lithographic and evaporation processes. The values of a and w were $100\,\mu\mathrm{m}$ and $1000\,\mu\mathrm{m}$, respectively.

The transmission characteristics of the line sample thus formed were investigated over the frequency range of 400-4000 MHz through the standing-wave measurements of the open-circuit and the short circuit driving-point impedances of the sample. A strip-line measurement system similar to that described in Reference (5) was used for the purpose.

The measured values of λ_g/λ_0, $Re(Z_0)$ and α are plotted vs. frequency in Figs. 7, 8 and 9, respectively. The results clearly indicates the presence of the slow-wave mode region at lower frequencies where λ_0/λ_g takes values as large as 15 or thereabouts. Such a large value of the slowing factor, corresponding to the effective dielectric constant of 225, could not be explained by any other possible form of propagation. Since the theoretically expected values of γ_0/λ_g, $Re(Z_0)$ and f_0 of the sample are about 30, 14 ohms and 160 MHz, one could say that the

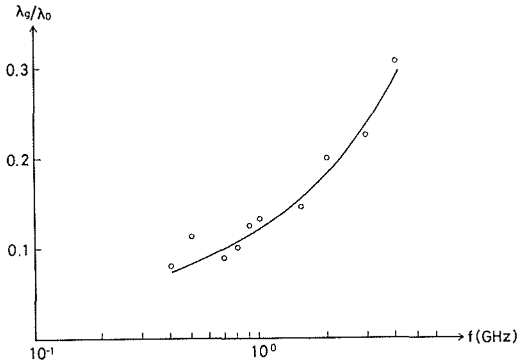

Fig. 7 Measured Values of λ_g/λ_0 vs. Frequency

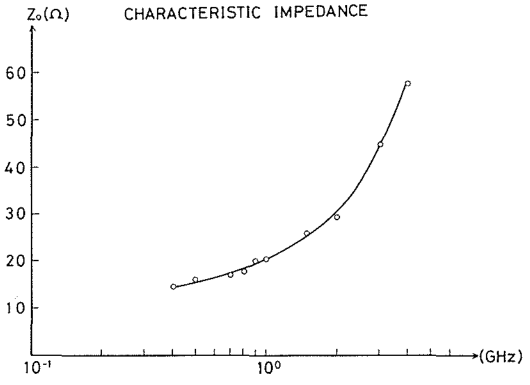

Fig. 8 Measured Values of $Re(Z_0)$ vs. Frequency

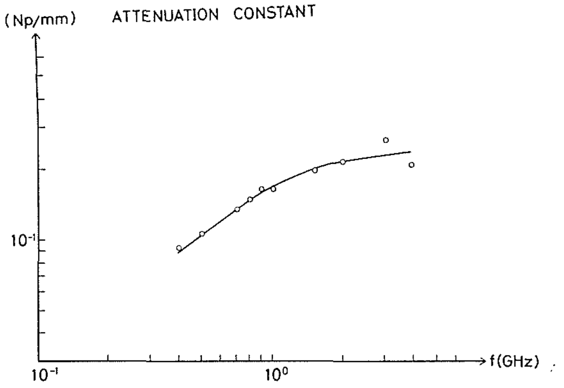

Fig. 9 Measured Values of α vs. Frequency

agreement between theory and experiment is fairly good in spite of the fact that the measured lowest frequncy is still slightly higher than the cut-off frequency of the slow-wave mode. To increase the value of f_0 and obtain better characteristics in the GHz region, one must fabricate a much more miniaturized lines as is predicted by the present theory. More detailed experiments on such optimized lines are in progress now and their results will be presented in a later report.

5. Conclusions

A new type of coplanar strip waveguide on a semiconducting substrate is described, which is potentially very useful for monolithic integration of microwave semiconductor devices and also for construction of a new class of transmission-line type functional devices. Propagation modes, design principle and fundamental characteristics are clarified using a quasi-static approach. A preliminary experiment supports the validity of the basic theory. Further work is required to optimize the characteristics of the line both theoretically and experimentally.

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