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## Theory of Carrier Waves Along Semiconductor-Insulator Boundaries

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### Abstract

A new theory of carrier waves in semiconductors, formulated in the form of transverse resonance of transmission-line analogs, is presented. It enables one to discuss the wave propagation along a mixed system with semiconductor-insulator boundaries in a general manner. The boundary conditions associated with carrier diffusion are discussed in detail. Bulk and surface waves in the collision-dominant semiconductors are analyzed with a brief mention of possible convective instabilities and their mechanisms.

### 1. Introduction

It has been a dream of long standing for electrical and electronic engineers to construct solid-state analogs of travelling wave amplifiers and other vacuum devices based on similar principles. Except for the success in the bulk and surface acoustic wave amplifiers utilizing the piezoelectric coupling, no travelling-wave type device of purely electronic nature seems at the moment to have a right to claim its practical utility among various other standard types of electronic devices produced by the highly developed modern semiconductor technology. In fact, although numerous interesting and attractive ideas concerning new travelling wave devices were presented in the past<sup>1-14)</sup>, only a few of them were realized with unfortunately poorer performances than expected. One of the important reasons for this was obviously the limitations in the material and device technologies encountered in the device fabrication, but, another equally important reason was the imperfectness of the underlying theories. Some of the early understandings of the wave interactions in semiconductors were based on the collisionless vacuum-like approach, ignoring the collision-dominant nature of the plasma. It has also been a rather common practice up to now to ignore the effect of carrier diffusion<sup>2,7,15)</sup>, pushing the devices down into the zero temperature limit. When the effect of diffusion is considered, there have been several different approaches employed by different authors, apparently leading to contradicting results, as will be discussed in detail later.

The purpose of the present paper is to describe a new frame of theory on the carrier waves associated with single-carrier flows in finite semiconductor slabs at finite temperatures. Such a theory will enable one to check the feasibility of various previous ideas on a more realistic basis, and will also serve as a tool to invent new

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functional devices suitable to the silicon planar integrated device technology. In fact, the results on the surface carrier waves discussed later indicate the possibility of low-loss propagation of surface waves along the inversion layer of the semiconductor surface, and if such is the case, the silicon-siliconoxide system, which is now well controllable by the modern MOS technology, would become the future playground of carrier waves, resulting in a novel and useful class of functional devices. Another unique feature of the present theory is that it is formulated in the form of what is called transverse resonance method<sup>16)</sup> by microwave engineers, and consequently the handling of the complicated boundaries is greatly facilitated by the transmission line concepts.

## 2. Electromagnetic Fields in Extrinsic Semiconductors with Drifting Carriers

A uniform  $n$ -type semiconductor is considered throughout the paper. A single carrier flow with a positive space charge background of ionized donors is assumed and any possible effects arising from electron-hole interactions are ignored. All the electrons are assumed to have the same average drift velocity  $v_d$  in the  $z$  direction. The electromagnetic fields in the semiconductor are then determined by combining Maxwell's equations and charge-current equations with the following kinetic equation for electrons based on the phenomenological fluid model of plasmas<sup>1)</sup>.

$$\frac{d\mathbf{v}}{dt} = -\frac{q}{m^*}(\mathbf{E} + \mathbf{v} \times \mathbf{B}) - \nu \mathbf{v} - \frac{kT_e}{m^*} \frac{1}{n} \nabla n \quad (1)$$

where  $\mathbf{v}$ : electron velocity  $m^*$ : electron effective mass  
 $T_e$ : electron temperature  $\nu$ : collision frequency  
 $n$ : electron density.

If one assumes small-signal fluctuations of wave nature, propagating in the drift direction with a factor of  $\exp(j\omega t - j\beta z)$ , to all the field quantities as well as to the density  $n$  and the velocity  $\mathbf{v}$  of the electrons, the following differential equation for the small signal electric field vector is obtained after a little algebra;

$$\begin{aligned} & \left[ \nabla^2 + \frac{\omega^2}{c^2} \left( 1 - \frac{\omega_p^2}{\omega(\omega - \beta v_d - j\nu)} \right) \right] \mathbf{E} \\ & = j \frac{\omega^2}{c^2} v_d (\nabla \cdot \mathbf{E}) + j \frac{\omega_p^2}{c^2(\omega - \beta v_d - j\nu)} v_d \times \nabla \times \mathbf{E} + \left( 1 - \frac{\omega \nu D}{c^2(\omega - \beta v_d - j\nu)} \right) \nabla (\nabla \cdot \mathbf{E}) \end{aligned} \quad (2)$$

where  $\left\{ \begin{array}{l} c = \frac{1}{\sqrt{\epsilon \mu}} : \text{light velocity} \\ \omega_p = \sqrt{\frac{q^2 n_0}{m^* \epsilon}} : \text{plasma frequency } (n_0 \text{ is } d. c. \text{ carrier density}) \\ D = \frac{kT_e}{m^* \nu} : \text{diffusion constant, } v_d : \text{drift velocity vector} \end{array} \right.$

In order to simplify the notations, it is convenient to introduce here the

following two quantities.

$$\omega_c^* = -j \frac{\omega_p^2}{\omega - \beta v_d - j\nu} \quad (3a)$$

$$\lambda_D = \sqrt{\frac{\epsilon k T}{n_0 q^2}} = \sqrt{\frac{D}{\omega_c}} : \text{ Debye length} \quad (3b)$$

where  $\omega_c$  is the dielectric relaxation frequency.

### 2.1 Waves in Semiconductors with Infinite Cross-section

When the cross-section of the semiconductor is infinite, the problem is essentially one-dimensional, and the existence of the following two types of waves are recognized by putting  $\mathcal{V}=(0, 0, -j\beta)$  in Equation (2).

(1) a transverse electromagnetic wave (TEM wave) without  $E_z$  and  $H_z$  components which is characterized by the dispersion relation of

$$\beta^2 - \frac{\omega^2}{c^2} \left(1 - \frac{\omega_c^*}{\omega}\right) - j \frac{\omega_c^* \beta v_d}{c^2} = 0 \quad (4)$$

(2) a longitudinal wave with an  $E_z$  component, which is characterized by the dispersion relation of

$$\beta^2 + j \frac{1}{\lambda_D^2} \frac{\omega - \beta v_d - j\omega_c^*}{\omega_c^*} = 0 \quad (5)$$

The wave (1) of the above is a solenoidal ( $\text{div } \mathbf{E}=0$ ) electromagnetic wave without space charge perturbation. On the other hand, the wave (2) is a space charge wave with a lamellar field ( $\text{rot } \mathbf{E}=0$ ), having no magnetic field component. The latter can be seen more clearly by taking the zero-temperature limit. By making  $\lambda_D \rightarrow 0$ , Equation (5) reduce to  $\omega - \beta v_d - j\omega_c^* = 0$ . When the inertial effect of electrons dominates the effect of collisions, one can put  $\omega_c^* = -j \frac{\omega_p^2}{\omega - \beta v_d}$ , and the resultant dispersion relation is readily shown to represent two kinds of space charge waves, i.e., the slow and fast waves in the theory of electron beam tubes. On the other hand, only one type of space charge wave results in the limit of the collision-dominant situation, which propagates synchronously with the drifting carriers. The dispersion relation is simply given by  $\omega - \beta v_d - j\omega_c = 0$ , where  $\omega_c = \frac{\omega_p^2}{\nu}$  is the dielectric relaxation frequency.

### 2.2 Waves in Semiconductors with Finite Cross-section

A general analysis of the wave propagation in semiconductors with finite dimensions is extremely complicated and beyond the scope of the present treatment. The wave propagation along a mixed system that possesses a finite number of such semiconductor-insulator boundaries as shown in Fig. 1, is the main subject of the present paper. In Fig. 1, the boundary is assumed to have an infinite extension in the  $xz$ -plane, and only transverse magnetic waves (TM waves) are considered, which have non-vanishing electric field components in the direction of the drift motion. The problem is now essentially two-dimensional, and the waves are represented by a set of three field components,  $E_z$ ,  $E_y$  and  $H_x$ . With the use of Equation (4), one

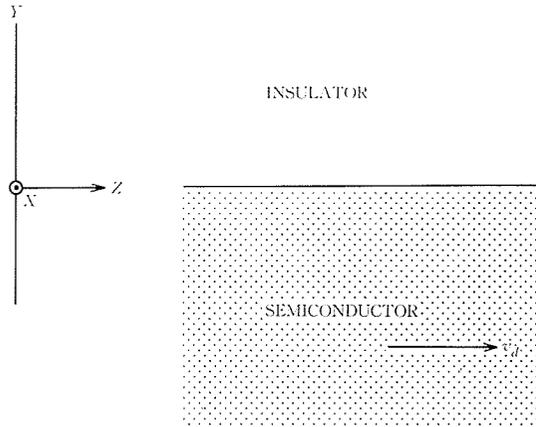


Fig. 1. Semiconductor-Insulator Interface and Co-ordinate System.

can show<sup>17)</sup> that two types of waves emerge again as in the case of the infinite cross-section. They are quasi-solenoidal ( $\text{div } \mathbf{E} \simeq 0$ ) and quasi-lamellar ( $\text{rot } \mathbf{E} \simeq 0$ ) waves coupled by a term which is proportional to  $(v_d/c)^2$ , and which can be ignored under the realistic conditions the carrier saturation velocities in semiconductor materials. This is a slight generalization of Sumi's argument<sup>10)</sup> to include the case of inertia-dominant situation at high frequencies. The above types of waves are hereafter referred to as the *s*-wave and *l*-wave, respectively. If one assumes exponential variations of the field components in the *y*-direction as represented by  $\exp(-\Gamma_s y)$  and  $\exp(-\Gamma_l y)$  for *s*- and *l*- waves, respectively, the two waves are characterized by the following relations.

$$\Gamma_s^2 = \beta^2 - \frac{\omega^2}{c^2} \left( 1 - \frac{\omega_c^*}{\omega} \right) - j \frac{\omega_c^* \beta v_d}{c^2} \quad (6 \text{ a})$$

$$\Gamma_l^2 = \beta^2 + j \frac{1}{\lambda_D^2} \frac{\omega - \beta v_d - j \omega_c^*}{\omega_c^*} \quad (6 \text{ b})$$

The surface impedance of each wave looking into in the negative *y*-direction, where semi-infinite extension of semiconductor is assumed as shown in Fig. 1, can be defined by  $Z \equiv -E_z/H_x|_{y=0}$  (negative sign is attached by the power flow convention), and is obtained for each wave as follows, using Maxwell's field equations.

$$Z_{0s} = \frac{\Gamma_s}{j\omega\epsilon} \frac{1}{1 - j \frac{\omega_c^*}{\omega}} \quad (7 \text{ a})$$

$$Z_{0l} = \frac{\beta}{j\epsilon v_d \Gamma_l} \quad (7 \text{ b})$$

### 3. Boundary Conditions

In order to discuss the wave propagation in a mixed system of semiconductors and insulators, suitable boundary conditions should be known at the insulator-semiconductor interface. For the sake of simplicity, an ideal interface without surface recombination and trapping, being subjected to the flat-band condition, is assumed here, and the mobility reduction near the surface is also ignored. It is

now well known that such an ideal situation can be more or less realized by the use of the advanced silicon technology.

The relevant quantities for the boundary conditions under such simplifications are then the surface charge density  $\rho_s$  and the surface current density  $J_s$  at the surface of the semiconductor. Previous treatments on the carrier waves assume, in the limit of zero temperature, what is known as Hahn boundary conditions<sup>18)</sup> in the theory of electron beam tubes. It is stated as follows :

$$\rho_s = \frac{qn_0 v_{ys}}{j(\omega - \beta v_d)} \quad (8a)$$

$$J_s = \rho_s v_d \quad (8b)$$

where  $v_{ys}$  is the  $y$ -component of the small-signal velocity at the surface.

On the other hand, when the effects of thermal diffusion of carriers are taken into consideration, different approaches have been used by different authors in a rather confusing manner. Some of the ideas employed previously are listed below :

- (1) M. Sumi<sup>10)</sup> assumed  $\rho_s=0$  and  $J_s=0$  at the boundary.
- (2) K. Bløtekjaer<sup>19)</sup> used the boundary conditions of continuity of the tangential components of the electric displacement vector and the vanishing normal component of the conduction current at the interface.
- (3) Y. Mizushima *et al.*<sup>11)</sup> assumed  $J_s=0$ , but at the same time, the presence of the scalloped charge given by Equation (8a) was also assumed when the signal frequency was in the neighborhood of the dielectric relaxation frequency.
- (4) C. Hervouet<sup>20)</sup> and M. Kawamura *et al.*<sup>21)</sup> assumed non-zero values of  $\rho_s$  and  $J_s$  at the boundary, and the effects of carrier diffusion were discussed with the use of a modified Hahn boundary condition given by

$$\rho_s = \frac{n_0 \rho v_{ys}}{j(\omega - \beta v_d) + \omega_c (\beta \lambda_n)} \quad (9)$$

As is known, the boundary conditions for electromagnetic fields that involve the surface charge and surface current are as follows :

$$\varepsilon_1 E_{y1} - \varepsilon_2 E_{y2} = \rho_s \quad (10a)$$

$$H_{x1} - H_{x2} = J_s \quad (10b)$$

where the suffix 1 refers to the insulator and the suffix 2 refers to the semiconductor with reference to Fig. 1. From the charge continuity at the interface, the following condition should also be satisfied.

$$j\omega\rho_s = j\beta J_s + J_{ys} \quad (11)$$

where  $J_{ys}$  is the normal component of the conduction current density at the interface.

From Equations (10) and (11), one can see that (1) and (2) of the above four approaches are equivalent and they are in a strong conflict with (3) and (4).

Since it is apparent that the boundary conditions have a supreme importance for the waves which are to propagate along the interface, the above disagreement deserves a careful examination.

First of all, one should note that either of the surface charge and surface current is not a physical existence in the strict sense, but both are merely mathematical devices to describe the physical situation where charge and current have more concentrated values near the surface than in the bulk. In the mathematical terms,  $\rho_s$  and  $J_s$  are defined by  $\rho_s = \lim_{\Delta x \rightarrow 0} (\Delta x) \rho$  and  $J_s = \lim_{\Delta x \rightarrow 0} (\Delta x) J$ . In a physical sense, however, this  $\Delta x$  cannot be zero in its absolute meaning, since each electron is known to possess its finite extension in the real space represented by its wave function. Therefore, the criterion for the usefulness of the concepts of surface charge and current should lie in the comparison of the thickness  $\Delta x$  of such a concentrated charge or current layer with other important parameters associated with the wave propagation, such as the wave length and the dimensions of the media.

Since it is assumed here that the semiconductor surface is a free surface, one must always take account of the possibility of having a charge perturbation near the surface as one of the degrees of freedom of motion. Therefore, it may be reasonable to apply the concepts of surface charge and current to describe such a perturbation phenomenologically in the case of zero-temperature limit. However, when the effects of carrier diffusion are to be analyzed, the charge perturbation widened by the carrier diffusion has a thickness typically of the order of the Debye length, which is no longer negligible as compared with the wave length. Hence, such a perturbation should be described as a volume charge variation with the use of the  $l$ -wave and not by the artificial surface charge and current.

Thus, the present discussion justifies the approaches (1) and (2) of the previous works. The approach (3) is apparently self-inconsistent, and the approach (4) can be shown to be impertinently ignoring the carrier diffusion from the surface into the bulk in the derivation of Equation (9), although one would have expected the largest effect of diffusion there according to the Fick's law of diffusion.

The inevitable conclusion of the above discussion is that the  $s$ -wave and  $l$ -wave represented by Equations (6a) and (6b) cannot be excited separately but should always be combined together so as to fulfill the boundary conditions of Equations (9)~(11) with  $J_s=0$  and  $\rho_s=0$ . From the solutions of the Maxwell's field equations, one can show that the ratio of  $H_x$  of  $l$ -wave to that of  $s$ -wave should then be given by

$$r_l \equiv \frac{H_{x2l}}{H_{x2s}} = - \frac{j\omega_e \beta v_d}{(\omega - \beta v_d)(\omega - j\omega_c^*)} \quad (12)$$

The complete boundary conditions are satisfied by further asking for the transverse resonance of the surface impedances at the interface, which in turn leads to the establishment of the dispersion equation of the carrier waves. For the evaluation of the surface impedance of the insulator, the following well-known relations can be applied.

$$Z_{0i} = \frac{j\omega \epsilon_1}{I_i}, \quad I_i^2 = \beta^2 - \frac{\omega^2}{c_1^2} \quad (13)$$

where  $I_i$  is the decay rate of the wave into the insulator.

#### 4. Surface Impedance of Semiconductor Slabs and General Dispersion Equation

##### 4.1 Surface Impedance of a Semi-infinite Semiconductor Lump

A transmission line analog of the semiconductor-insulator interface shown in Fig. 1 is illustrated in Fig. 2, where the line voltage and current on the line are defined by  $V_s \equiv \sqrt{1+\eta} E_{sz}$ ,  $I_s \equiv \sqrt{1+\eta} H_{sx}$  for  $s$ -wave, and  $V_l \equiv (\sqrt{1+\eta}/\sqrt{\eta}) E_{lz}$ ,  $I_l \equiv (\sqrt{1+\eta}/\sqrt{\eta}) H_{lx}$  for  $l$ -wave. In the insulator, only  $s$ -wave is present and one obtains  $V_i = E_{iz}$  and  $I_i = H_{ix}$  by putting  $\eta=0$  in the definition of  $V_s$  and  $I_s$ .

From Fig. 2, the surface impedance of the semi-infinite semiconductor lump is given by

$$Z = \frac{1}{1+\eta} Z_{0s} + \frac{\eta}{1+\eta} Z_{0l} \quad (14)$$

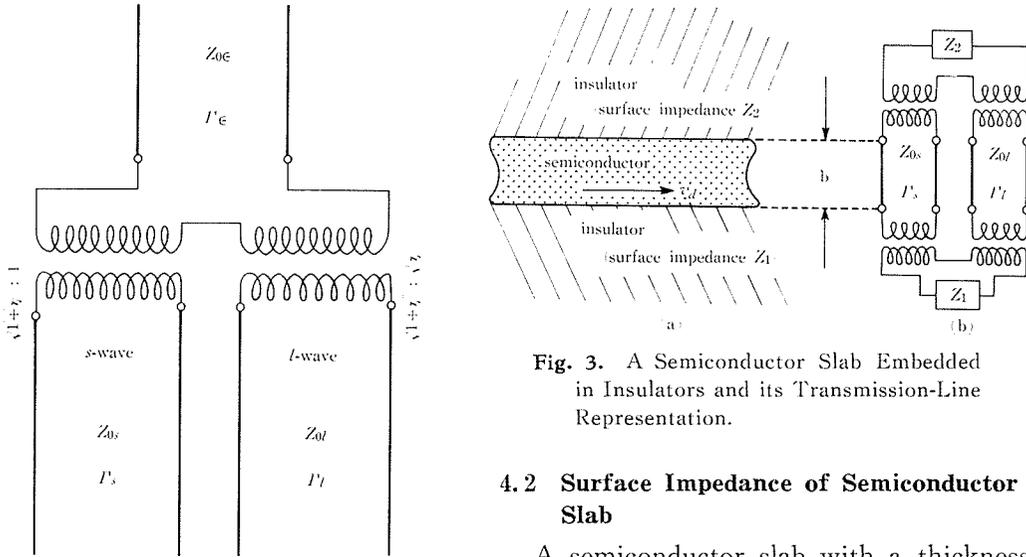


Fig. 3. A Semiconductor Slab Embedded in Insulators and its Transmission-Line Representation.

##### 4.2 Surface Impedance of Semiconductor Slab

A semiconductor slab with a thickness,  $b$ , sandwiched by two semi-infinite insulators with different surface impedances  $Z_1$  and  $Z_2$  is considered, as shown in Fig. 3(a). The transmission-line analog of such a structure is given in Fig. 3(b). By the analysis of this transmission line system, the surface impedance of the semiconductor slab attached to a semi-infinite insulator with the surface impedance  $Z_1$  is obtained as

$$Z = \frac{Z_1 + Z_{sh}}{Z_1 + Z_{0p}} Z_{0p} \quad (15)$$

where  $Z_{sh}$  and  $Z_{0p}$  are the surface impedance for the case of  $Z_1=0$  and  $Z_1=\infty$ , respectively.  $Z_{sh}$  and  $Z_{0p}$  are given by

$$Z_{sh} = \frac{1}{1+\eta} Z_{0s} \tanh \Gamma_s b + \frac{\eta}{1+\eta} Z_{0l} \tanh \Gamma_l b + \frac{\eta}{1+\eta} \left( \frac{1}{\cosh \Gamma_s b} - \frac{1}{\cosh \Gamma_l b} \right)^2 \frac{1}{\frac{\eta}{Z_{0s}} \tanh \Gamma_s b + \frac{1}{Z_{0l}} \tanh \Gamma_l b} \quad (16 a)$$

$$Z_{0p} = \frac{1}{1+\eta} Z_{0s} \coth \Gamma_s b + \frac{\eta}{1+\eta} Z_{0i} \coth \Gamma_i b \quad (16 \text{ b})$$

Equation (15) indicates that the semiconductor slab is equivalent to a single transmission line with the characteristic impedance  $\sqrt{Z_{sh} Z_{0p}}$  and the propagation constant  $\frac{1}{b} \tanh^{-1} \sqrt{Z_{sh}/Z_{0p}}$ .

### 4.3 Dispersion Equation

The dispersion equation of the waves along the semiconductor slab is then obtained by substituting Equation (15) into  $Z_2 + Z = 0$  (transverse resonance), and the resultant equation is

$$Z_1 Z_2 + (Z_1 + Z_2) Z_{0p} + Z_{sh} Z_{0p} = 0 \quad (17)$$

In the case of a symmetric structure with  $Z_1 = Z_2 \equiv Z_0$ , this equation is further split two equations given by

$$Z_0 + Z_{\pm} = 0 \quad (18 \text{ a})$$

where

$$Z_+ = \frac{1}{1+\eta} Z_{0s} \coth \Gamma_s a + \frac{\eta}{1+\eta} Z_{0i} \coth \Gamma_i a \quad (\text{anti-symmetric}) \quad (18 \text{ b})$$

$$Z_- = \frac{1}{1+\eta} Z_{0s} \tanh \Gamma_s a + \frac{\eta}{1+\eta} Z_{0i} \tanh \Gamma_i a \quad (\text{symmetric}) \quad (18 \text{ c})$$

and

$$b = 2a$$

These two types of waves are identified as anti-symmetric and symmetric modes, respectively, because of the anti-symmetric and symmetric distributions of the longitudinal electric field component  $E_z$  with respect to the center of the slab.

## 5. Carrier Waves in Collision-Dominant Semiconductors

The theoretical formulations given in the previous sections are of general nature, and the effects of carrier diffusion, inertia and collision are all included. It also includes the electromagnetic waves and space charge waves, no matter whether they are bulk waves or surface waves.

In this section, a specific case of carrier waves which propagate approximately synchronously with the drift motion in the collision-dominant semiconductor is discussed in more detail. For this purpose, the collision-dominant approximation  $\omega_c^* = \omega_c$  and the slow-wave approximation  $\Gamma_s = \beta$  are used.

### 5.1 Carrier Waves in Zero-Temperature Limit

The symmetric mode which propagates along the semiconductor slab with a symmetric dielectric loading is considered. On taking the limit of  $\lambda_D \rightarrow 0$  carefully in Equations (6a) and (18b), we can obtain two types of waves. One is a solenoidal surface wave with a surface charge, whose dispersion relation is given by

$$\beta = \frac{\omega - jF\omega_c}{v_d} \quad (19 \text{ a})$$

where

$$F \equiv \frac{1}{1 + (\epsilon_1/\epsilon) \coth \beta a} \quad (19 \text{ b})$$

and  $\epsilon_1$  is the permittivity of the loading insulators.  $F$  is the space-charge reduction factor familiarly known in the theory of electron beam tubes.

The other type of the solution is the bulk wave with volume charge perturbation. It has the same dispersion relation with that of the one-dimensional space charge wave which has been hitherto successfully used in the coupled mode theory of acoustic wave amplification<sup>22)</sup>. The dispersion relation is as follows ;

$$\beta = \frac{\omega - j\omega_c}{v_d} \quad (20)$$

The value of  $\Gamma_l$  which gives the cross-sectional variation of the field is determined by the following equation, discarding the trivial degenerate solution of  $\Gamma_l = \beta$ .

$$\Gamma_l \tanh \Gamma_l a = \beta \tanh \beta a \quad (21)$$

It may readily be seen that there exists an infinite number of nearly pure imaginary solutions for  $\Gamma_l$  corresponding to quasi-sinusoidal variations of the fields of the bulk waves. In a recent publication<sup>15)</sup> on a similar analysis, T. Koike *et al.*, denied the existence of such bulk waves, which is physically difficult to accept, if one considers the success of the one-dimensional theory of acoustic wave amplification<sup>22)</sup>.

## 5.2 Carrier Waves at Finite Temperatures

In this case, the dispersion relation of the symmetric mode surface wave propagating along the semiconductor slab, is given by

$$\beta = \frac{\omega - jF\omega_c}{v_d \left( 1 + j \frac{\omega_c}{\Gamma_l v_d} (1 - F) \frac{\tanh \beta b}{\tanh \Gamma_l b} \right)} \quad (22)$$

where a gross approximation of  $\Gamma_l \simeq \frac{1}{\lambda_p}$  may be used.

On the other hand, the bulk wave solutions can be obtained by combining Equation (22) with Equation (6b), in quest again of nearly pure imaginary values of  $\Gamma_l$ .

It is seen from Equation (22) that a thin slab of semiconductor is desirable to obtain low-loss propagation of surface carrier waves, and in this sense, the use of the inversion layer of silicon-silicondioxide system is an interesting possibility.

## 5.3 Convective Instability of Surface Carrier Waves

One of the important advantages of the present transverse resonance formulation is that it enables one to analyze various possible surface wave interactions in a straightforward way in terms of the wall impedance.

As an example, let us consider a structure where a semiconductor slab with the thickness  $2a$  is symmetrically loaded with impedances walls whose surface imped-

ances are both given by  $\frac{\beta}{j\omega\varepsilon_1} X(\omega, \beta)$ . The dispersion relation of the symmetric mode surface carrier wave along such a system is obtained as

$$\beta = \frac{\omega - j \left( \frac{X \tanh \beta b}{1 + X \tanh \beta b} \right) \omega_c}{v_a \left( 1 + j \frac{\omega_c}{\Gamma_i v_a} \frac{\tanh \beta b}{\tanh \Gamma_i b} \cdot \frac{1}{1 + X \tanh \beta b} \right)} \quad (23)$$

One of the interesting conclusions which can be drawn from the study of Equation (23) is that the necessary condition for the convective instability of the wave is to put inductive impedance walls. Such inductive impedance walls can be provided not only by the electromagnetic slow-wave structure, or travelling piezoelectric waves, but also by semiconductors under a magnetic field or even by resistive semi-metal walls. It also implies that the surface impedance of a semiconductor under the growing-wave condition, is capacitive, and therefore it suggests that the parallel-semiconductor amplifier proposed by Y. Mizushima *et al.*<sup>11)</sup> is impossible to realize, according to the present theoretical frame. The reason why an inductive wall is required, can be understood by the power flow analysis. By putting an inductive wall, the phase of the collisions are adjusted in such a way that the energy loss due to collisions are reduced by the excitation of the wave, or, in other words, a situation of negative collision loss from the d. c. average results as a consequence of such a phase adjustment. Hence, the instability here is essentially collision-induced, and the mechanism is quite different from what happens in electron beams, where a negative kinetic power flow takes place and contributes to the instability.

## 6. Conclusions

A new frame of theory to analyze the carrier waves along semiconductor-insulator interfaces is presented in the form of a transverss transmission-line approach. Specific cases in the collision-dominant semiconductor seem to require further detailed discussions with numerical computations. These results will be presented later in another paper. Further generalization of the theory to include the cases of two-carrier stream and magneto-plasma is clearly feasible on the basis of the present theory. In fact, an effort towards such a direction has already been made by Hasegawa *et al.* in a specific case<sup>23)</sup>, which has shown the importance of the boundary conditions at the interface. A more generalized formulation is being developed at the moment, and will be the subject of another paper.

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### References

- 1) Steele, M. C.: Wave Interaction in Solid-State Plasmas McGraw-Hill (1969).
- 2) Kino, G. S.: IEEE Trans. Electron Devices, ED-17 (1970), p. 178.
- 3) Solymer, L. and Ash, E. A.: Int. J. Electronics, 20 (1966), p. 127.
- 4) Collins, J. H., Lakin, K. M., Quate, C. F. and Shaw, H. J.: Appl. Phys. Lett., 13 (1968), p. 314.
- 5) Coldren, L. A. and Kino, G. S.: Appl. Phys. Lett., 8 (1971), p. 317.
- 6) Burke, B. E. and Kino, G. S.: Appl. Phys. Lett., 9 (1968), p. 310.
- 7) Robinson, B. B.: IEEE Trans. Electron Devices, ED-17 (1970), p. 200.
- 8) Hines, M. E.: IEEE Trans. Electron Devices, ED-16 (1969), p. 88.
- 9) Gandhi, O. P. and Grow, R. W.: IEEE Trans. Electron Devices, ED-18 (1971), p. 853.
- 10) Sumi, M.: Jap. J. Appl. Phys., 6 (1967), p. 688.
- 11) Mizushima, Y. and Sudo, T.: IEEE Trans. Electron Devices, ED-17 (1970), p. 541.
- 12) Swanenburg, T. J. B.: IEEE Trans. Electron Devices, ED-20 (1973), p. 630.
- 13) Verma, K. B. and Gandhi, O. P.: IEEE Electron Devices, ED-20 (1973), p. 855.
- 14) Okamoto, H. and Mizushima, Y.: Jap. J. Appl. Phys., 9 (1970), p. 113 (in Japanese).
- 15) Koike, T. Yokoo, Y. and Ono, S.: Trans. Inst. Electron. Com. Eng. Jap., 58-B (1975), p. 187.
- 16) Collins, J. H.: Field Theory of Guided Waves, McGraw-Hill. (1960).
- 17) Hasegawa, H. and Yamanaka, T.: Inst. Electron. Com. Eng. Jap., Transation of Microwave Group MW 72-43 (1972), (in Japanese).
- 18) Hahn, W. C.: Gen. Elec. Rec. 42 (1939), p. 258.
- 19) Bløtekjaer, K.: IEEE Trans. Electron Devices, ED-17 (1970), p. 30.
- 20) Hervouet, C.: Phys. Stat. Sol., 34 (1969), p. 501.
- 21) Kawamura, M. and Takayama, K.: Trans. Inst. Electron. Com. Eng. Jap., 55-B (1972), p. 345.
- 22) Bløtekjaer, K. and Quate, C. F.: Proc. IRE, 52 (1964), p. 360.
- 23) Hasegawa, H. and Yamanaka, T.: Trans. Inst. Electron. Com. Eng. Jap., 57-C (1974), p. 19 (in Japanese).