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Interface excitations in metal-insulator-semiconductor structures*

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The interface excitations associated with the inversion layer of a metal-insulator-semiconductor structure are investigated. These excitations can be regarded as coupled modes whose components are the two-dimensional-electron-gas plasmon and the surface plasmon of the metal-insulator interface. The dependence of the coupled modes on the insulator thickness and the gate-electrode plasma frequency are studied.

I. INTRODUCTION

The plasma modes of an inversion layer on a semiconductor surface have been studied theoretically by several authors.[1-4] Stern[1] obtained the dispersion relation for the plasma modes of a two-dimensional electron gas embedded in a three-dimensional dielectric. His results are implicitly contained in the work of earlier investigators who considered plasma oscillations of thin metallic films,[5] if the film thickness is assumed to be sufficiently small. Fetter[2] has used a hydrodynamic approach to investigate the plasma oscillations of a two-dimensional electron gas. In the work of Stern, two parameters appear which characterize the plasma properties of the system. The first parameter, with the dimensions of an acceleration, is $a = 2\pi n_s e^2/m^*$, where n_s is the number of electrons per unit area of the two-dimensional electron gas, and m^* is the electron effective mass. The other parameter is ϵ_0, the dielectric constant of the insulating background in which the two-dimensional electron gas is embedded. If cq, the product of the velocity of light and the wave number of the plasma wave (along the surface) is small compared to a/c, then the plasmon frequency is given by $\omega \approx \epsilon_0^{-1/2} cq$. For $q \gg a/c^2$ (but still small compared to the Fermi-wave number k_F), the plasmon frequency is given by $\omega \approx (aq/\epsilon_0)^{1/2}$. This behavior is quite in contrast with the dispersion relation for plasmons in three dimensions, where $\omega \approx \omega_p[1 + O(qv_F/\omega_p)^2]$. The frequency $\omega_p = (4\pi ne^2/m^*)^{1/2}$ (where n is the number of electrons per unit volume) is usually large, so that the plasmon dispersion is rather small at long wavelengths. At the present time, the plasma modes of an inversion layer on a semiconducting surface have not been observed experimentally. This could be due, in part, to the fact that the model of a two-dimensional electron gas embedded in an infinite dielectric differs in a significant way from the experimental situation in a real metal-insulator-semiconductor (MIS) structure. The finite thickness of the insulator (whose dielectric constant ϵ_0 is different from the dielectric constant ϵ_s of the semiconducting substrate) which separates the semiconductor from the metallic gate electrode could affect the plasmon-dispersion relation. This question has been touched on by Nakayama,[4] who has studied the surface waves associated with surface carriers at the interface of two dielectric media. Nakayama has briefly discussed the three-media problem in an appendix of his paper. In this paper, we consider the three-media problem for a metal-insulator-semiconductor system in which the semiconductor inversion layer acts as a two-dimensional electron gas. We investigate how the "plasmon" of the two-dimensional electron gas is affected by the thickness of the insulating layer, and by the "surface-plasmon" frequency of the gate (metallic) electrode.

II. METAL-INSULATOR-SEMICONDUCTOR STRUCTURE

We consider a model which consists of a metal filling the space $z < 0$, a layer of dielectric between $z = 0$ and $z = d$, and a semiconductor filling the space $z > d$. At the plane $z = d$, the interface between the semiconductor and the insulator, there is a two-dimensional electron gas. The metal is represented by a simple-local-dielectric function $\epsilon_M = 1 - \omega_p^2/\omega^2$. The insulator and semiconductor have dielectric constants ϵ_0 and ϵ_s respectively. The two-dimensional electron gas has a polarizability $\underline{\chi}(q, \omega)$. By this we mean that an electric field of the form $\vec{E}(z)\, e^{i\omega t - iqy}$ evaluated at the plane $z = d$ will cause a polarization of the two-dimensional electron gas of the form $\vec{P}(r, t) = [P_x(q, \omega), P_y(q, \omega)]\,\delta(z-d)$, where $\vec{P}(q, \omega) = \underline{\chi}(q, \omega) \cdot \vec{E}$.

The wave equation describing the propagation of electromagnetic waves in the system can be written

$$\nabla\times(\nabla\times\vec{E}) = \omega^2\epsilon\vec{E} - 4\pi i\omega\vec{j} \quad . \tag{1}$$

Here and throughout the remainder of this paper we use units such that the velocity of light is equal to unity. In Eq. (1), ϵ is the dielectric constant appropriate to the medium in which the wave equation is being applied, and $\vec{j}(r,t) = \vec{j}(q,\omega)\, e^{i\omega t - iqy}\,\delta(z-d)$ is the current density associated with the two-dimensional electron gas. In fact, $\vec{j}(q,\omega)$ is equal to $i\omega\underline{\chi}(q,\omega)\cdot\vec{E}$. For z different from d, the wave equation is perfectly standard in form and the solutions can be written down immediately. We introduce subscripts M, 0, and S to refer to quantities appropriate to the metal, insulator, and semiconductor, respectively. Imposing the appropriate boundary conditions[3,4] at $z = \pm\infty$ and at the interfaces leads to the dispersion relation

$$\beta_S^{-1}\epsilon_S + \beta_0^{-1}\epsilon_0(e^{\beta_0 d} - \gamma e^{-\beta_0 d})(e^{\beta_0 d} + \gamma e^{-\beta_0 d})^{-1} + 4\pi\chi = 0 \quad , \tag{2}$$

where

$$\gamma = (\beta_M\epsilon_0 + \beta_0\epsilon_M)^{-1}(\beta_M\epsilon_0 - \beta_0\epsilon_M) \tag{3}$$

and

$$\beta^2 = q^2 - \omega^2\epsilon \quad . \tag{4}$$

The subscripts on β and ϵ in Eq. (3) are appropriate to the medium being considered. Equation (2) is the dispersion relation for waves localized in the interface. In the limit as d tends to infinity, the equation reduces to

$$4\pi\chi\,\beta_0\beta_S + \beta_0\epsilon_S + \beta_S\epsilon_0 = 0 \quad , \tag{5}$$

provided that γ remains finite. For $\epsilon_0 = \epsilon_S$, this equation reduces to

$$\epsilon_0 + 2\pi\beta\chi = 0 \quad . \tag{6}$$

This is exactly the dispersion relation for the plasmon in a two-dimensional electron gas embedded in a dielectric ϵ_0 which has been derived by Stern.[1] In all of these equations, $\chi(q,\omega)$ is the longitudinal polarizability $\chi_{yy}(q,\omega)$. In addition to the solution of Eq. (5), in the limit as $d\to\infty$, $\gamma\to\infty$ is also a solution. From Eq. (3) we see that this implies

$$\beta_M\epsilon_0 + \beta_0\epsilon_M = 0 \quad . \tag{7}$$

By substituting for β_M and β_0, we can easily show that Eq. (7) is equivalent to $q^2 = (\epsilon_0 + \epsilon_M)^{-1}\epsilon_0\epsilon_M\omega^2$, the dispersion relation for a surface plasmon at the metal-insulator interface.[6] In the general result, Eq. (2), these two modes are coupled, since the finite thickness of the insulator allows the exponentially decaying fields associated with each of the modes to have finite amplitude at the opposite side of the insulator layer. This result is identical to the dispersion relation obtained by Nakayama [his Eq. (A2)], if one identifies his surface charge $\sigma^{(s)}$ with $-i\omega\chi$. Although for large values of the wave number q the frequency of the surface plasmon at a metal insulator interface is large compared to the frequency of a two-dimensional electron gas plasmon with the same value of q, retardation effects cause both of the frequencies to approach zero linearly with q. In addition, the decay length β_0^{-1} of the waves in the insulator becomes quite large at low frequencies, so some effect of the coupling of the modes might be expected if the oxide thickness d is not too large. In addition, the fact that the interface modes are simple gate-electrode-insulator surface plasmons coupled to the plasmons of the two-dimensional electron gas, suggests that a gate electrode of different character from a high-electron density metal could lead to interesting effects.

III. METAL-INSULATOR-SEMICONDUCTOR PLASMONS

For a typical metal like aluminum, silver, or gold, the bulk plasma frequency is quite high, and as a first approximation, we can take $\epsilon_M = 1 - \omega_p^2/\omega^2$ equal to minus infinity. This means that we are considering frequencies much smaller than ω_p. In that case, γ approaches the value -1, and Eq. (2) simplifies to

$$4\pi\chi + \beta_S^{-1}\epsilon_S + \beta_0^{-1}\epsilon_0\coth\beta_0 d \simeq 0 \quad . \tag{8}$$

This result has actually been derived by Chaplik[7] in his study of crystallization of a two-dimensional electron gas into a Wigner lattice. He refers to the mode as the longitudinal acoustic mode of the two-dimensional electron gas.

In Fig. 1, we plot the dispersion relation [Eq. (2)] for the following values of the parameters: $\omega_p = 8\times10^{15}\ \mathrm{sec}^{-1}$, $N = 2\times10^{12}\ \mathrm{cm}^{-2}$, $m^* = 0.2m$, where m is the mass of a free electron, $\epsilon_S = 12$ and $\epsilon_0 = 3.7$. These values correspond approximately to a metal–silicon-dioxide–silicon structure with 2×10^{12} conduction electrons per cm^2 of the inversion layer. The four curves which appear in Fig. 1 correspond to values of the oxide thickness of 10^{-1}, 10^{-3}, 10^{-4}, and 10^{-5} cm, respectively. The thick-oxide result is indistinguishable from the dispersion relation for an infinite oxide thickness. Only one branch of the dispersion relation appears in Fig. 1. The second branch, which corresponds to the metal-oxide surface plasmon, occurs at much higher frequency and is almost unaffected by the presence of the two-dimensional electron gas a distance d away. It should be noted that the dispersion curves for the thinner oxides are almost straight lines. The velocity of the wave for the

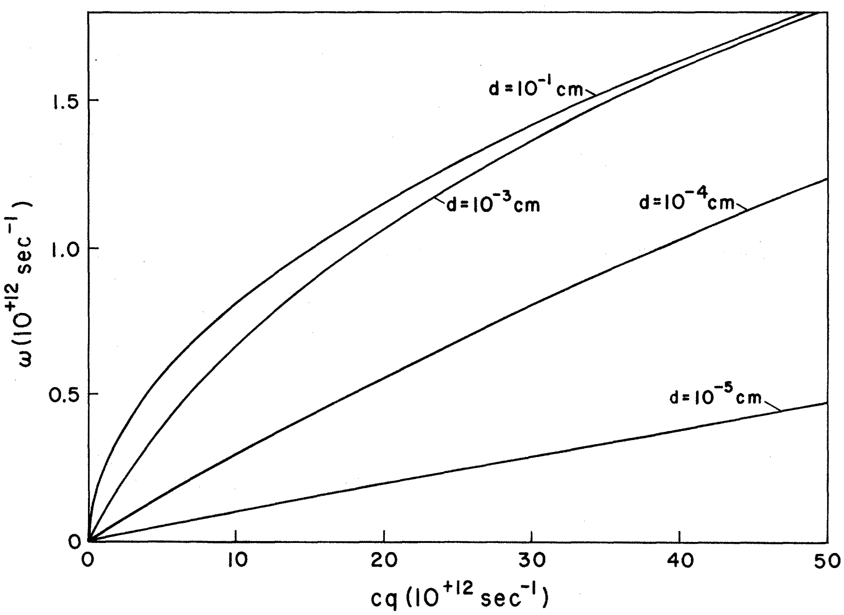

FIG. 1. Metal-insulator-semiconductor plasmon-dispersion relation [Eq. (2)] for four different values of the oxide thickness d. The other parameters that enter in Eq. (2) were given the following values: $\omega_p = 8 \times 10^{15}$ sec^{-1}, $N = 2\times 10^{12}$ cm^{-2}, $m^* = 0.2m$ (m being the free-electron mass), $\epsilon_S = 12$, and $\epsilon_0 = 3.7$.

10^{-5}-cm-thick oxide is approximately 1% of the velocity of light in vacuum.

IV. SEMIMETAL-INSULATOR-SEMICONDUCTOR PLASMONS

For the case of a metallic gate where $\omega_p \approx 10^{16}$ sec^{-1}, the surface plasmon of the metal-oxide interface had a frequency much higher than that of the two-dimensional electron gas. Because of this the coupling between the two modes, the metallic surface plasmon and the plasmon of the two-dimensional electron gas, was relatively weak. In fact, it is surprising how much the presence of the gate affects the dispersion of the low-frequency mode in this situation. If we replace the metal by a semimetal like bismuth of antimony, or in fact by a degenerate semiconductor whose bulk plasma frequency ω_p is of the order of ($\omega_p \approx 10^{+12}$ sec^{-1}), the frequencies of interest, then we might expect much more dramatic coupling effects. In Fig. 2, we show the dispersion relation for a semimetal-insulator-semiconductor case with $\omega_p = 2.5\times 10^{12}$ sec^{-1}. The other parameters are the same as given previously. In this figure, the two modes are rather weakly coupled, since it corresponds to a thick oxide with $d = 5\times 10^{-3}$ cm. The simplest way of understanding the result is to recall that the surface plasmon of the semimetal-oxide interface starts out at $q \simeq 0$, like $\omega = cq\epsilon_0^{-1/2} \simeq 0.46cq$. For large values of q, this mode tends toward the constant value $\omega_p(1+\epsilon_0)^{-1/2} \simeq 1.15\times 10^{+12}$ sec^{-1}. The plasmon of the two-dimensional electron gas behaves like $\omega \simeq (aq/\epsilon_0)^{1/2}$. These two curves would cross at $cq \approx 2\times 10^{13}$ sec^{-1} and $\omega \simeq 1.15\times 10^{12}$ sec^{-1}, if there were no coupling between them.

In Fig. 2, the higher-frequency mode has the character of a semimetal-oxide surface plasmon at very long wavelength and of a two-dimensional electron gas plasmon at short wavelengths. The opposite is true of the lower-frequency mode. In the vicinity of the "crossing," the two modes are strongly coupled and have mixed character.

V. DOUBLE-INVERSION-LAYER PLASMONS

Since the localized "plasma" modes of an MIS structure are simply coupled plasma modes which the two surfaces (M–I and S–I surfaces) would have at infinite separation, we might consider what kind of plasma modes could occur in a p-type-silicon-oxide-n-type-silicon sandwich in which inversion layers are present at both semiconductor surfaces. The method used to derive this dispersion relation is quite similar to that discussed for the MIS structure, so only the result will be given. The dispersion relation can be written

$$\left(4\pi\chi_1 + \frac{\epsilon_1}{\beta_1} + \frac{\epsilon_0}{\beta_0}\coth\beta_0 d\right) \times \left(4\pi\chi_2 + \frac{\epsilon_2}{\beta_2} + \frac{\epsilon_0}{\beta_0}\coth\beta_0 d\right) = \left(\frac{\epsilon_0}{\beta_0}\right)^2 \operatorname{csch}^2\beta_0 d \ . \quad (9)$$

Here χ_1 and χ_2 are the polarizabilities of the two inversion layers and ϵ_1 and ϵ_2 are the background dielectric constants of the n-type and the p-type semiconductors, respectively. As d tends to infinity, we obtain two independent modes

$$4\pi\chi_1 + \epsilon_1/\beta_1 + \epsilon_0/\beta_0 = 0 \quad (10)$$

and

$$4\pi\chi_2 + \epsilon_2/\beta_2 + \epsilon_0/\beta_0 = 0 \ ,$$

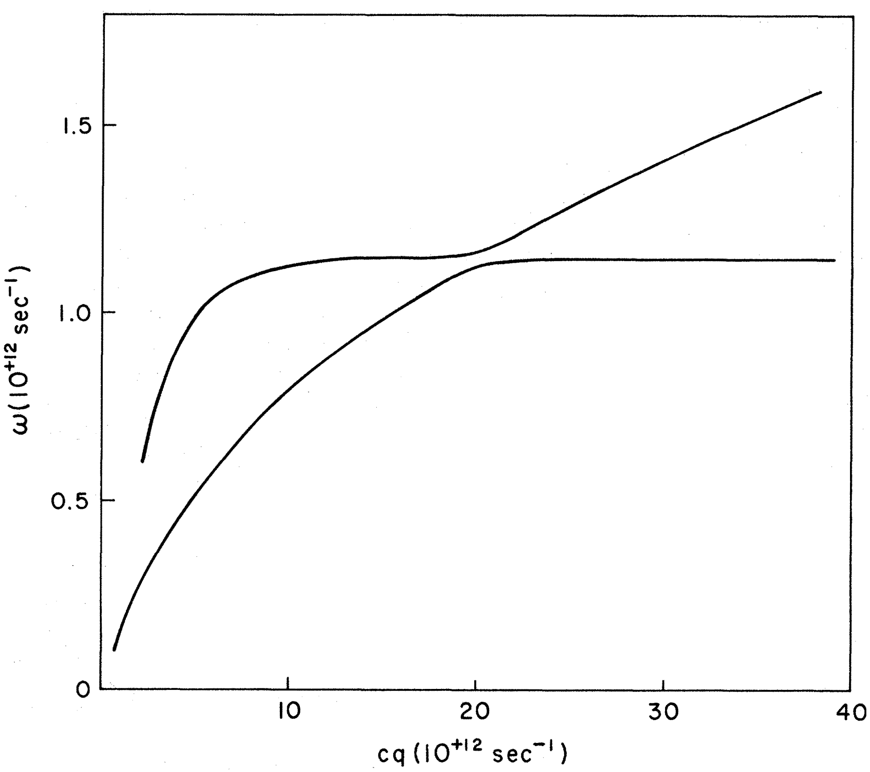

FIG. 2. Semimetal-insulator-semiconductor plasmon dispersion relation [Eq. (2)], for an oxide thickness $d = 5\times10^{-3}$ cm. Here $\omega_p = 2.5\times10^{12}$ sec^{-1}. The other parameters that enter in Eq. (2) are the same as in Fig. 1.

the plasmons of the two-dimensional electron gas and the two-dimensional hole gas, respectively. For finite values of the oxide thickness, these two modes are coupled. In Fig. 3, we present results for the case of $N_e = N_h = 2\times10^{12}\ \mathrm{cm}^{-2}$; $m_e^* = 0.2m$ $m_h^* \simeq 0.4m$, $\epsilon_1 = \epsilon_2 = \epsilon_S = 12$, and $\epsilon_0 = 3.7$. For $d = 10^{-1}$ cm, the two curves shown are essentially indistinguishable from the results for infinite separation [Eq. (10)]. The dashed curve in Fig. 3 represents the two-dimensional electron-gas plasmon,

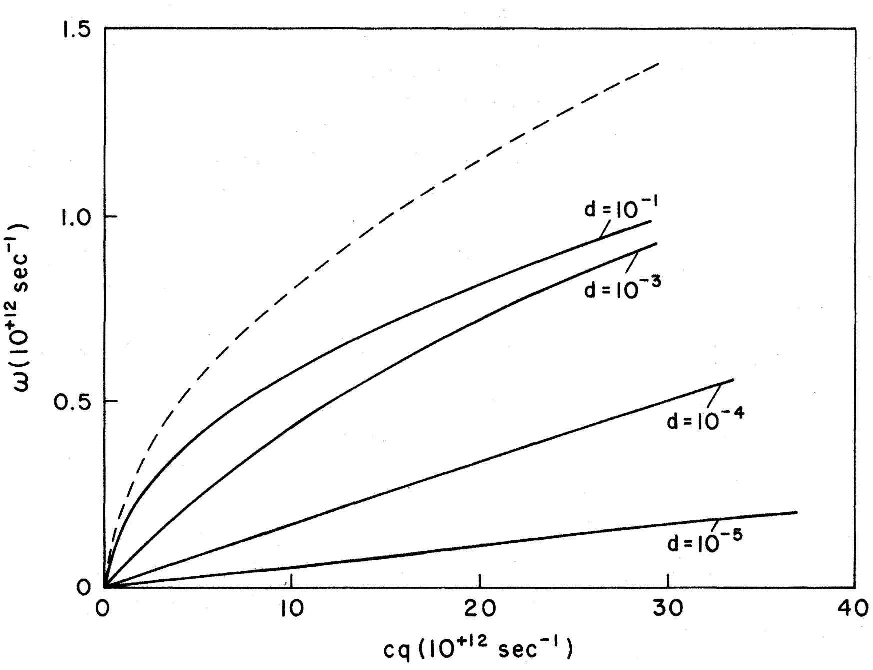

FIG. 3. Double-inversion-layer plasmon-dispersion relation [Eq. (9)] for four different values of the oxide thickness d. The other parameters that enter in Eq. (9) were given the values $N_e = N_h = 2\times10^{12}$ cm^{-2}, $m_e^* = 0.2m$, $m_h^* \simeq$ $\simeq 0.4m$, $\epsilon_1 = \epsilon_2 = \epsilon_S = 12$, and $\epsilon_0 = 3.7$. The dashed curve represents the two-dimensional electron-gas plasmon, and the solid curves represent the two-dimensional hole-gas plasmon.

while the solid curves are the two-dimensional hole-gas plasmon for different values of the oxide thickness. The latter occur at lower frequency, since the hole mass is heavier than the electron mass. As the oxide thickness is decreased, the electron-gas plasmon is essentially unaffected by the coupling, but the hole-gas dispersion relation is pushed to lower frequency. The sequence of solid curves shows the dispersion relation for this mode for $d = 10^{-1}$, 10^{-3}, 10^{-4}, and 10^{-5} cm.

VI. SUMMARY

We have studied the "plasma" modes of a two-dimensional electron gas in the inversion layer of an MIS structure. We find that even for quite thick oxide layers, the dispersion relation of the two-dimensional-electron-gas plasmon can be altered appreciably. The plasma modes of the MIS structure are simply coupled metal-insulator surface plasmon and two-dimensional electron-gas plasmons. For a typical metal like aluminum, the surface-plasmon frequency is so high compared to the frequency of the two-dimensional electron-gas plasmon, that the coupling is relatively weak. Despite this, the frequency of the two-dimensional electron-gas plasmon is strongly affected by the presence of the gate electrode as shown in Fig. 1. For a semimetal or degenerate semiconductor gate, the surface plasmon frequency of the gate-oxide interface can fall in the same range as the frequency of the two-dimensional-electron-gas plasmon. In that case, strong coupling between the plasmon modes occurs even for very large oxide separations. Finally, the coupled modes of a double inversion layer are studied.

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[1]F. Stern, Phys. Rev. Lett. 18, 546 (1967).

[2]A. Fetter, Ann. Phys. (N.Y.) 81, 367 (1973).

[3]K. W. Chiu and J. J. Quinn, Phys. Rev. B 9, 4724 (1974).

[4]M. Nakayama, J. Phys. Soc. Jpn. 36, 393 (1974).

[5]See, for example, R. H. Ritchie, Phys. Rev. 106, 874 (1957).

[6]K. W. Chiu and J. J. Quinn, Nuovo Cimento B 10, 1 (1972).

[7]A. V. Chaplik, Zh. Eksp. Teor. Fiz. 62, 746 (1972) [Sov. Phys.-JETP 35, 395 (1972)].