Charge-Density Excitations at the Surface of a Semiconductor Superlattice: A New Type of Surface Polariton

Gabriele F. Giuliani[(a)] and J. J. Quinn
Brown University, Providence, Rhode Island 02912
(Received 23 June 1983)

A new type of surface polariton, which can occur at the surface of a semiconducting superlattice, is introduced. Because of the quantization of the electron energy levels by the superlattice potential this new polariton mode has the remarkable property of being free from Landau damping.

PACS numbers: 71.36.+c, 71.45.-d, 73.40.Lq

Electromagnetic modes which propagate along the interface between two media with different dielectric properties and which involve photons coupled to dipole excitations are called surface polaritons.[1] In simple metals and degenerate semiconductors, which are well approximated by a jellium model, the surface plasmon-polariton occurs at a frequency ω_{sp} which is always smaller than the bulk plasmon frequency ω_p.[2] Because the presence of the surface destroys the lattice translational invariance, surface plasmons in these systems can always excite electron-hole pairs, and they are thus subject to Landau damping.[3] Both in semiconducting and metallic superlattices the bulk plasmon spectrum[4,5] is rich in structure. In the former the single-particle spectrum is characterized by quantized electronic minibands. In the quantum limit, in which only the lowest miniband is occupied, there can exist both intrasubband and intersubband collective modes. The frequency of these modes depends in different ways on $\vec{q}$ and k, the components of wave vector parallel and perpendicular to the superlattice layers, respectively. The existence of this rich structure in the bulk excitation spectrum gives rise to a novel set of surface polariton modes[6] with the remarkable property of being free of Landau damping. The surface polariton frequency for a given value of $\vec{q}$ can occur either above or below the bulk plasmon continuum, depending on the ratio of the background dielectric constants of the semiconductor and the bounding material. In the case of polar semiconductors the electric field of the excitations gives rise to plasmon-phonon interaction resulting in coupled surface plasmon-phonon polaritons. Because this new type of surface polariton has never been observed experimentally, the object of this note is to elucidate a few of its remarkable properties in the hope of stimulating experiment.

The simplest model of a superlattice which correctly describes the intrasubband plasma modes[7] consists of a periodic array of two-dimensional electron-gas layers imbedded in a material of background dielectric constant ϵ_s. In this model the miniband structure of the superlattice is neglected, and only the ground subband and the intrasubband collective modes are considered.[8] The bulk plasmon spectrum can most easily be obtained by writing the general solution of the wave equation in the regions between the electron layers, assuming that $\vec{E}(z+na)=\exp(ikna)\vec{E}(z)$, where a is the superlattice period, and imposing the standard electromagnetic boundary conditions at each of the two-dimensional electron layers. For $q \ll k_F$, k_F being the Fermi wave vector of a two-dimensional electron gas, and $\omega \ll qk_F\hbar/m$, the resulting dispersion relation is given by

$$\omega^2(q,k)=(1/2\epsilon_s)qa\,S(q,k)\omega_p{}^2. \qquad (1)$$

Here ω_p is the effective three-dimensional plasma frequency, $\omega_p{}^2=4\pi n_s e^2/ma$, where n_s is the number of electrons per unit area in any layer. $S(q,k)=\sinh qa\,\{\cosh qa-\cos ka\}^{-1}$ is a structure factor. For small values of the parameter qa, corresponding to strong coupling between the layers, a band of plasma modes results with frequencies $\omega(q,k)$ between $\omega_+(q)=\omega(q,0)$ and $\omega_-(q)=\omega(q,\pi/a)$. This band appears as the upper shaded region in Fig. 1, a plot of frequency ω vs wave vector q.

In order to describe surface excitations we assume that the periodic array of two-dimensional electron layers described above fills the space $z>0$, while an insulator of dielectric constant ϵ_0 fills the space $z<0$. We follow exactly the same prescription of writing down solutions of the wave equation in each region and imposing standard boundary conditions at the planes $z=na$ for $n=0,1,2,\ldots$. However, in this case we are interested in the situation in which the electric

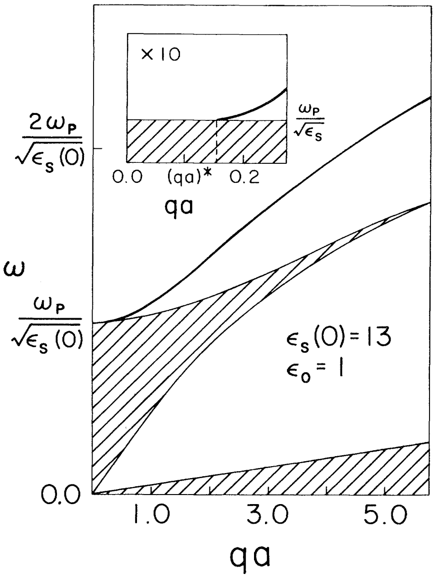

FIG. 1. A plot of frequency vs qa, the product of wave number parallel to the layers and superlattice spacing. The upper shaded region is the band of bulk intrasubband plasmons. The lower shaded region is the single-particle continuum. The surface polariton mode is the solid line which intersects the bulk plasmon continuum at $(qa)^* = 0.154$ as shown in the inset.

field in the region $z > 0$ satisfies the relation $\vec{E}(z + na) = e^{-\alpha na}\vec{E}(z)$, where α has a positive real part. In addition, the boundary condition at $z = 0$ is different from those at $z = na$ for $n \geq 1$, because of the abrupt change in background dielectric constant from ϵ_s to ϵ_0, and because only the decaying-wave solution is allowed in the region $z < 0$. In the electrostatic or nonretarded limit ($cq \gg \omega$) the resulting dispersion relation is

$$[1 - e^{(\alpha+q)a}][\epsilon_+ - v_q \chi(q, \omega)] + [1 - e^{(\alpha-q)a}][\epsilon_- + v_q \chi(q, \omega)] = 0. \qquad (2)$$

Here α, the inverse of the penetration depth, is the complex value of k for which the bulk dispersion relation [Eq. (1)] is satisfied for the given value of q and ω. We have introduced the symbols $\chi(q, \omega)$, the polarizability of the two-dimensional electron gas; $v_q = 2\pi e^2/q$, the Fourier transform of the two-dimensional Coulomb interaction; and $\epsilon_\pm = \frac{1}{2}(\epsilon_s \pm \epsilon_0)$. The solution of Eq. (2), which must be obtained numerically, depends in an important way on the ratio of ϵ_s to ϵ_0. For $\epsilon_s > \epsilon_0$ the parameter α is real, and the surface mode occurs at a frequency above the bulk plasmon continuum. For large values of qa, α is equal to q, but it decreases to zero as q decreases to the value q^*. Thus, for wavelengths short compared to superlattice period, the penetration depth is one wavelength, while for $q \simeq q^*$, the penetration depth becomes infinite. For $\epsilon_s < \epsilon_0$, α acquires an imaginary part (equal to π/a) and the surface mode falls below the continuum. The result is illustrated by the solid curve in Fig. 1 which corresponds to a semiconductor-vacuum interface with $\epsilon_s = 13$ and $\epsilon_0 = 1$. It is interesting to note that the frequency of the surface mode intersects the bulk plasmon continuum at a finite value of the wave vector q; an enlargement of the region of intersection is shown in the inset. The intersection with the continuum occurs at a value of $q = q^*$ given by

$$q^* = a^{-1}\ln|(\epsilon_s + \epsilon_0)/(\epsilon_s - \epsilon_0)|. \qquad (3)$$

For $q < q^*$ surface modes do not exist because the decay parameter α is purely imaginary. As ϵ_s approaches ϵ_0 the value of q^* increases logarithmically, so that the existence of surface modes depends quite critically on the difference in background dielectric constants of the semiconducting superlattice and the bounding medium. If the first two-dimensional electron layer occurs a small distance (compared to the superlattice period) from the interface, the value of q^* is increased as would be expected. We have obtained numerical results for the case in which $\epsilon_0 > \epsilon_s$; the surface mode lies below the continuum and intersects the lower edge at a value of q^* given by Eq. (3).

In a three-dimensional jellium model, a surface plasmon of wave vector $\vec{q}$, parallel to the surface, and frequency ω can always decay into an electron-hole pair conserving both energy and the parallel component of the wave vector. The reason for this is that the electronic energy spectrum is a continuous function of k, the normal wave number, and any change in k is allowed because the presence of the surface relaxes the condition of wave-vector conservation. In the semiconducting superlattice, however, the quantization of the electronic energy levels by the superlattice potential makes it impossible to conserve energy and parallel wave vector in the creation of an electron-hole pair by an elementary excitation lying outside the single-particle continuum. For the simple model used in this note, the single-particle continuum consists of that portion of the ω-q plane in which $\omega < \hbar q(k_F + q/2)2m$. The single-particle continuum appears as the lower shaded region in Fig. 1. For the model considered in Ref. 4, there are a number of "two-dimensional" electronic subbands separated by energy $\hbar\omega_{n0}$ from the ground subband, and there can exist a set of intersubband collective modes. In that case, there are additional regions of the single-particle continuum defined by $-\hbar q(k_F - q/2)/2m + \omega_{n0} < \omega < \hbar q(k_F + q/2)/2m + \omega_{n0}$ for each subband separation ω_{n0}. Collective surface excitations lying outside the single-particle continuum are unable to decay into a single electron-hole pair and are thus not subject to Landau damping. Therefore, in high-mobility semiconducting superlattices, these surface modes should have a very long lifetime.

A good candidate for possible observation of the surface polariton modes discussed here is the GaAs-$Al_xGa_{1-x}As$ superlattice system.[9] In this system the background dielectric function ϵ_s is not a constant, but it is a function of frequency: $\epsilon_s(\omega) = \epsilon_s(\infty)(\omega^2 - \omega_L^2)(\omega^2 - \omega_T^2)^{-1}$, where $\epsilon_s(\infty)$ is the high-frequency dielectric constant, and ω_L and ω_T are the longitudinal and transverse optical phonon frequencies respectively. By taking account of the frequency dependence of $\epsilon_s(\omega)$, we find a system of coupled bulk intrasubband-plasmon–optical-phonon bands, as shown by the two upper shaded regions in Fig. 2. The plasmon continuum is very similar to that in Fig. 1 in which coupling to phonons is neglected. The bulk longitudinal optical phonon mode becomes dispersive, and is broadened into a band by coupling to the plasmons. The parameters used in the numerical calculation are $\epsilon_s(\infty) = 10.9$, $\epsilon_s(0) = (\omega_L^2/\omega_T^2)\epsilon_s(\infty) = 13$, and $\epsilon_0 = 1$; the values of ω_L and ω_p are taken to be 5.5×10^{13} $\sec^{-1}$ and 3.13×10^{13} $\sec^{-1}$ respectively. The solid lines represent the coupled surface plasmon-phonon polariton modes. Again, we observe the plasmonlike mode above the bulk continuum for values of q larger than some critical value.[10]

The phononlike mode begins below the bulk phonon continuum, but the coupling to the plasmon forces it to merge with the continuum and eventually to reappear above it at a larger value of q.

Because the surface polaritons are nonradiative, they do not couple directly to light. In order to observe the modes in optical absorption or reflectance it will be necessary to destroy the translation invariance along the surface by, for example, producing a grating on the surface. The grating spacing l should satisfy the inequality $l < 2\pi q^{*-1}$; this is in the range of thousands of

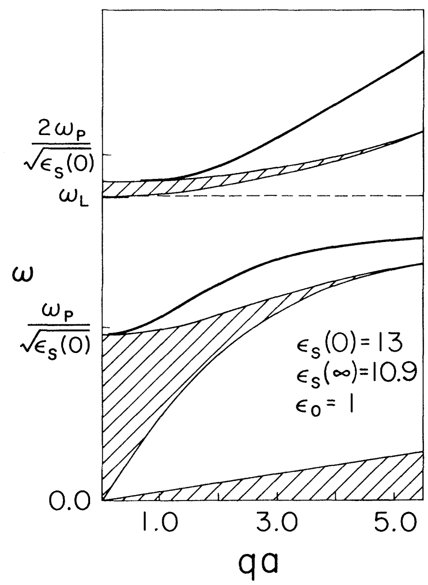

FIG. 2. Same plot as Fig. 1 when coupling to optical phonons is included. The two upper shaded regions are bulk intrasubband-plasmon–phonon modes. The two solid curves are the coupled surface polariton modes. The phononlike polariton intersects the continuum from above, and reappears below the continuum for very small values of wave vector.

angstroms and should not be difficult to achieve. The relatively large values of q^* make attenuated total reflection seem an unlikely method of observation. However, resonant Raman scattering[11] and electron-energy-loss spectroscopy appear to be possible techniques for observing these surface polaritons. In these experiments large momentum transfer along the surface is possible, so that values of q greater than q^* can be attained.

The authors would like to thank Professor Guoyi Qin, Dr. G. Gonzalez de la Cruz, and Dr. A. C. Tselis for stimulating discussions. This work was supported in part by the National Science Foundation through Grant No. DMR-81-21-069 and by the U. S. Office of Naval Research.

[a]On leave from the Scuola Normale Supériore, Pisa, Italy.

[1]E. Burstein, in *Polaritons*, edited by E. Burstein and F. DeMartini (Pergamon, New York, 1974), p. 1.

[2]R. H. Ritchie, Phys. Rev. 106, 874 (1957); E. A. Stern and R. A. Ferrell, Phys. Rev. 120, 130 (1960).

[3]R. Fuchs and K. L. Kliewer, Phys. Rev. B 3, 2270 (1971); D. E. Beck, Phys. Rev. B 4, 1555 (1971).

[4]A. Tselis, G. Gonzalez de la Cruz, and J. J. Quinn, Solid State Commun. 46, 779 (1983); G. Gonzalez de

la Cruz, A. Tselis, and J. J. Quinn, J. Chem. Phys. Solids 44, 807 (1983).

[5]G. Giuliani, J. J. Quinn, and R. F. Wallis, Bull. Am. Phys. Soc. 28, 448 (1983); A. Caille, M. Banville, P. D. Loly, and M. J. Zuckerman, Solid State Commun. 41, 119 (1982); see also the review by E. Tosatti, in *Interaction of Radiation with Condensed Matter* (International Atomic Energy Agency, Vienna, 1977), Vol. 1, pp. 281–294.

[6]Surface plasma modes of a superlattice consisting of metallic layers, which can be described by a local three-dimensional dielectric function, separated by insulating layers have been considered recently by R. E. Camley and D. L. Mills, Bull. Am. Phys. Soc. 28, 408 (1983). Related problems of acoustic and magnetic excitations in semi-infinite periodic structures have been investigated by R. E. Camley, B. Djafari-Rouhani, L. Dobrzynski, and A. A. Maradudin, Phys. Rev. B 27, 7318 (1983); and R. E. Camley, T. Rahman, and D. L. Mills, Phys. Rev. B 27, 261 (1983).

[7]A. L. Fetter, Ann. Phys. (N.Y.) 81, 367 (1973); S. Das Sarma and J. J. Quinn, Phys. Rev. B 25, 7603 (1982).

[8]A more realistic model is introduced in Ref. 4; the surface modes associated with intersubband excitations will be considered in another publication.

[9]For a type-II superlattice like the GaSb-InAs system the surface polariton modes have been studied by G. Qin, G. Giuliani, and J. J. Quinn, to be published.

[10]The behavior of α, the inverse penetration depth, is more complicated in this situation. See G. Giuliani, G. Qin, and J. J. Quinn, in Proceedings of the Fifth International Conference on the Electronic Properties of Two-Dimensional Systems, Oxford, 1983 (to be published); and G. Qin, G. Giuliani, and J. J. Quinn, to be published.

[11]See, for example, D. Olego, A. Pinczuk, A. C. Gossard, and W. Weigmann, Phys. Rev. B 25, 7867 (1982); Z. J. Tien, J. M. Worlock, C. H. Perry, A. Pinczuk, R. L. Aggerwal, H. L. Stormer, A. C. Gossard, and W. Weigmann, Surf. Sci. 113, 89 (1982). Although values of qa up to approximately 0.6 were achieved, no surface modes were observed. We believe that this results from the last electronic layer being separated from the surface by a GaAlAs overlayer of unspecified thickness. An overlayer of background dielectric constant equal to the bulk value dramatically increases the value of q^* as mentioned in the text.