Undamped surface magnetoplasma polaritons in superlattices

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(Submitted 10 January 1987; resubmitted 4 May 1987)
Pis'ma Zh. Eksp. Teor. Fiz. **45**, No. 12, 589–591 (25 June 1987)

Surface magnetoplasma polaritons exist at the boundary between the superlattice and the dielectric under conditions corresponding to the quantum Hall effect.

Superlattices in which a quantum Hall effect is observed have recently been synthesized.[1,2] Under the conditions corresponding to the quantum Hall effect, the dissipative components of the conductivity tensor of the superlattice vanish, with the result that bulk magnetoplasma oscillations are undamped.[3–6] At the boundary between the superlattice and the dielectric, electromagnetic oscillations of a different type occur: surface magnetoplasma polaritons.[7–9] These polaritons play an important role in the wave processes which occur in bounded semiconductor structures and can be utilized to study the characteristics of superlattices. Under the conditions corresponding to the quantum Hall effect of surface magnetoplasma polaritons at the boundary between the superlattice and the dielectric, we would expect to see several unusual properties due to the quantized nature of the Hall conductivity and the absence of dissipation in the medium.

 0021-3640/87/120751-04$01.00

We consider a superlattice ($y<0$) bordering a dielectric with a dielectric constant ϵ_d ($y>0$). A static external magnetic field $\mathbf{H}_0$ is directed along the axis of the superlattice (the z axis) and lies in the plane of the interface ($y=0$). Surface magnetoplasma polaritons with a frequency ω and a two-dimensional wave vector $\vec{\kappa}=(k_x,0,k_z)$ propagate at an arbitrary angle θ with respect to $\mathbf{H}_0$ ($k_x=\kappa\sin\theta, k_z=\kappa\cos\theta$). We describe the electromagnetic properties of the superlattice under the conditions of the quantum Hall effect by an effective dielectric tensor $\epsilon_{ij}(\omega)$, whose nonzero components are $\epsilon_{xx}=\epsilon_{yy}=\epsilon_{zz}=\epsilon_0$, $\epsilon_{xy}=-\epsilon_{yx}=-i(4\pi\sigma/\omega)H\ \mathrm{sign}(\mathbf{H}_0,\vec{\eta})$ for frequencies below the cyclotron frequency ω_c. Here ϵ_0 is the dielectric constant averaged over a distance greater than the period of the superlattice, d; η is a unit vector along the z axis; $\sigma_H=e^2S/hd$ is the Hall conductivity; e is the charge of an electron; h is Planck's constant; and S is an integer. Our choice of $\epsilon_{ij}(\omega)$ is fundamentally different from that in the Drude model, which was used in Refs. 10–13 and which leads to several new effects in the propagation of surface magnetoplasma polaritons: the absence of damping; quantization of resonant frequencies, phase velocities and transmissions bands; etc.

When the magnetoplasma waves are propagating at an arbitrary angle from $\mathbf{H}_0$, the electromagnetic field in the superlattice is a superposition of ordinary and extraordinary waves with transverse wave numbers [an arbitrary component A_j of the electromagnetic field in the superlattice can be written $A_j=(A_{j1}e^{ik_{y1}y}+A_{j2}e^{ik_{y2}y})e^{i(k_xx+k_{zz}-\omega_t)}$]

$$k^2_{y1,2}=-\alpha\pm\sqrt{\alpha^2-\beta}, \tag{1}$$

where

$$\alpha=\kappa^2-\frac{\omega^2}{c^2}\left(\epsilon_0+\frac{\epsilon^2_{xy}}{\epsilon_0}\right),$$

$$\beta=\left(\kappa^2-\frac{\omega^2}{c^2}\epsilon_0\right)^2-\frac{\omega^2}{c^2}\frac{\epsilon^2_{xy}}{\epsilon_0}\left(k^2_x-\frac{\omega^2}{c^2}\epsilon_0\right).$$

In a dielectric, the transverse wave number of the surface magnetoplasma polaritons is found from the equation $k^2_{yd}=(\omega^2/c^2)\epsilon_d-\kappa^2$.

Depending on the values of α and β, we find different types of magnetoplasma polaritons: bulk polaritons ($k^2_{y1,2}>0$), pseudosurface polaritons ($k^2_{y1,2}$— different signs), and true surface polaritons ($k^2_{y1,2}<0$).[11] The boundaries of the regions in which the various types of magnetoplasma polaritons exist are determined from the condition $\beta=0$. In the Voigt geometry ($\theta=\pm\pi/2$), the magnetoplasma polaritons may be either the bulk type or the true surface type. The latter are TM (extraordinary) waves with a transverse wave number which can be found from the equation $k^2_{ys}=-k^2_x+(\omega^2/c^2)[\epsilon_0+(\epsilon^2_{xy}/\epsilon_0)]$. We restrict the rest of this paper to true surface magnetoplasma polaritons.

The dispersion relation $\omega(\kappa,\theta,H_0)$ describing the propagation of these waves can be found by making use of the continuity of the tangential components of the electric and magnetic fields at the $y=0$ boundary and the decay of these components as $y\to\pm\infty$ (we are assuming that $\mathrm{Im}k_{y1,2}<0$ but $\mathrm{Im}k_{yd}>0$).[10-13] It follows from the dispersion relation that the propagation of true surface magnetoplasma polaritons is a nonreciprocal process; i.e., we have $\omega(\kappa,-\theta,H_0)\neq\omega(\kappa,\theta,H_0)$ and $\omega(\kappa,\theta,-H_0)\neq\omega(\kappa,\theta,H_0)$. In the region $\theta>0$ the true surface polaritons experience a resonance ($\kappa\to\infty$; the waves become electrostatic) at the frequency $\omega_{sp}(\theta)=(4\pi\sigma_H/\epsilon_0+\epsilon_d)\sin\theta$. The resonant frequency of the true surface polaritons is thus quantized, and it is independent of H_0 in the plateau of the Hall conductivity.[1)] The expressions which we have found for $\omega_{sp}(\theta)$ agree with the corresponding results of Ref. 8 if we assume $\omega\ll\omega_c$, $qa\ll1$, $pa\ll1$, $q=\sqrt{q^2+p^2}\sin\theta$, $n_s=(eH_0/hca)S$, where θ is the angle between the propagation direction of the wave and the direction of $\mathbf{H}_0$. In the region $\theta<0$, the true surface polaritons exist only at $\theta=-(\pi/2)$, and their propagation is a nonresonant process. In other words, a limiting frequency exists in the limit $\kappa\to\infty$.

Figure 1 shows the spectrum of true surface magnetoplasma polaritons in terms of the relative quantities $\xi=\omega\epsilon_0/4\pi\sigma_H$ and $\eta=\kappa c\epsilon_0/4\pi\sigma_H$. The regions in which the magnetoplasma polaritons exist are specified for $\theta=\pm\pi/4$. At $\theta=\pi/2$, dispersion curve 1 starts from the origin, and as n increases, it asymptotically approaches the relative frequency $\xi_{sp}(\pi/2)=[\omega_{sp}(\pi/2)\epsilon_0/4\pi\sigma_H]$. This curve lies entirely in the region of true surface polaritons, since the lower branch of the equation $\beta(\pi/2)=0$ is not a boundary line for TM wave. At $\theta=\pi/4$, the spectral line (dispersion curve 2) begins at the lower branch of the equation $\beta(\pi/4)=0$, at the point of the conversion of the pseudosurface polariton into the true surface polariton. During oblique propagation, there accordingly exists a low-frequency region of a nontransmission of surface waves in the spectrum of true secondary magnetoplasma polaritons. The magnitude of this region is quantized. As θ decreases, the point at which the spectrum of true surface polaritons begins shifts toward the origin of coordinates; i.e., the gap of nontransmission of surface waves becomes narrower. Dispersion curve 3 corresponds to

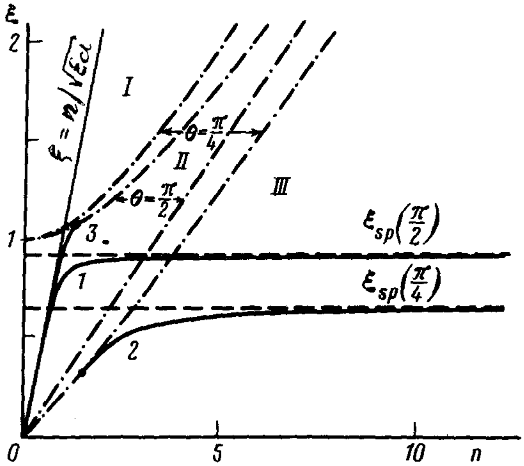

FIG. 1.

true surface polaritons at $\theta = -\pi/2$. It begins at the origin of coordinates and terminates on the line $\beta(-\pi/2) = \beta(\pi/2) = 0$. In the Faraday geometry ($\theta = 0$), there are no true surface magnetoplasma polaritons.

For the boundary between the superlattice and vacuum, with an effective electron mass $m^* = 0.068m_0$ in the semiconductor structure, with $d = 230$ Å, with $\epsilon_0 = 11.5$, and in a magnetic field $H_0 = 10$ T, the resonant frequency of the true surface magnetoplasma polaritons, $\omega_{sp}(\pi/2)$, with $S = 1$ is 1.5×10^{13} s^{-1}. On the other hand, we have $\omega_c = 2.6\times10^{13}$ s^{-1}. Clearly, the condition $\omega \sim \omega_{sp}(\theta) \ll \omega_c$ becomes satisfied by a progressively wider margin as H_0, d, or ϵ_d increases or as θ decreases.

We wish to stress that in the absence of damping the phase velocity of true surface magnetoplasma polaritons near the resonant frequencies may be very low. This circumstance might be utilized in various applications in microelectronics, e.g., in exciting surface waves by charged-particle beams that pass over superlattices.

[1)]The quantum frequencies of bulk electromagnetic waves (helicons) in an unbounded superlattice in the limit of a homogeneous medium ($\kappa d \ll 1$) are given in Refs. 5 and 6.

[1]H. L. Stömer, J. P. Eisenstein, A. C. Gossard, W. Wiegman, and K. Baldwin, Phys. Rev. Lett. **56**, 85 (1986).
[2]S. Takaoka, F. Nihei, K. Murase, A. Ishida, and H. Fujiyasu, J. Phys. Soc. Jpn. **55**, 2519 (1986).
[3]V. I. Tal'yanskiĭ, Pis'ma Zh. Eksp. Teor. Fiz. **43**, 96 (1986) [JETP Lett. **43**, 127 (1986)].
[4]L. Bendler and M. I. Kaganov, Pis'ma Zh. Eksp. Teor. Fiz. **44**, 345 (1986) [JETP Lett. **44**, 445 (1986)].
[5]A. Tselis, G. G. De la Gruz, and J. J. Quinn, Solid State Commun. **47**, 43 (1983).
[6]A. Tselis and J. J. Quinn, Phys. Rev. B **29**, 2021 (1986).
[7]Wu Ji-Wei, P. Hawrylak, G. Eliasson, J. J. Quinn, and A. L. Fetter, Solid State Commun. **58**, 795 (1986).
[8]Wu Ji-Wei, P. Hawrylak, G. Eliasson, and J. J. Quinn, Phys. Rev. B **33**, 7091 (1986).
[9]Wu Ji-Wei, G. Eliasson, and J. J. Quinn, Solid State Commun. **58**, 799 (1986).
[10]K. W. Chiu and J. J. Quinn, Nuovo Cimento **10**, 1 (1972).
[11]R. F. Wallis, J. J. Brion, E. Burstein, and A. Hartstein, Phys. Rev. B **9**, 3434 (1974).
[12]N. N. Beletskiĭ and V. M. Yakovenko, Poverkhnost'. Fiz. Khim. Mekhan. No. 2, 8, 1985.
[13]N. N. Beletskiĭ, E. A. Gasan, and V. M. Yakovenko, Preprint No. 282, Institute of Radiophysics and Electronics, Academy of Sciences of the Ukrainian SSR, 1985.

Translated by Dave Parsons