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Giant Surface Acoustic Wave Attenuation in the Quantum Hall Regime Inducedby a DC Current

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1. Introduction

The interaction between surface acoustic waves (SAWs) traveling on the surface of a GaAs-$Al_{1-x}Ga_xAs$ heterojunction and the two-dimensional electron gas (2DEG) confined at the heterointerface gives rise to an attenuation of the SAWs.[1,2] The attenuation coefficient κ is given by the longitudinal conductivity σ_{xx} of the 2DEG as

$$\frac{\kappa}{q} = \frac{K_{\mathrm{eff}}^{2}}{2} \frac{\sigma_{xx}/\sigma_m}{1+(\sigma_{xx}/\sigma_m)^2}, \qquad (1)$$

where q is the wave number of the SAWs, $K_{\mathrm{eff}}^2/2$ the electromechanical coupling coefficient, and $\sigma_m \approx \varepsilon v_s$ with ε and v_s being the dielectric constant and the sound velocity, respectively.[3] The attenuation is maximum when $\sigma_{xx} = \sigma_m$ with $A = \exp[-\pi(K_{\mathrm{eff}}^2/2)(L/\lambda_{\mathrm{SAW}})]$, where L and λ_{SAW} are the length of the SAW-2DEG interaction region and the wavelength of the SAWs, respectively. In GaAs, the maximum attenuation is rather small because of the small $K_{\mathrm{eff}}^2/2$ (= 6.5×10^{-4} for the (001) surface and [110] propagation). From the application point of view, greater SAW amplitude modulations are preferable. One obvious way to achieve this is to use materials having large values of $K_{\mathrm{eff}}^2/2$, like $LiNbO_3$ and $LiTaO_3$. In this case, however, a thin GaAs-$Al_{1-x}Ga_xAs$ heterojunction has to be fused onto the substrate to enable us to control the SAW attenuation electrically.[4]

In this paper, we report the experimental observation of a giant SAW attenuation in a conventional GaAs-$Al_{1-x}Ga_xAs$ heterojunction. The observation is made in an asymmetric double quantum well system in the presence of a dc current. The attenuation in the two-layer system far exceeds the prediction by Eq. (1). We provide evidences that suggest the interlayer electron transfer be responsible for the gigantic SAW amplitude modulation.

2. Experimental

Figure 1 shows a schematic of our experimental devices. A 0.2 mm wide and 1 mm long mesa of a GaAs-$Al_{0.3}Ga_{0.7}As$ heterojunction is placed between two interdigital transducers (IDTs) that operate at a frequency of about 1.5 GHz. We have employed asymmetric double quantum well structures, in which the second subband is occupied by a small number of electrons when the electron density is increased using the persistent photoconductivity effect.[5] One of the IDTs launches SAWs. Following the SAW-2DEG interaction that takes place while the SAWs propagate on the surface of the mesa, the SAWs are detected by the other IDT. The mesa is equipped with Ohmic contacts, which are used to inject a current through the 2DEG. As σ_m in GaAs is extremely small (3.5×10^{-7} Ω^{-1}), we apply a magnetic field perpendicular to the 2DEG to realize the condition $\sigma_{xx} \sim \sigma_m$.[1,2] Generally, $\sigma_{xx} \gg \sigma_m$ at zero magnetic field. However, σ_{xx} becomes almost zero at the quantum Hall states. The measurements were carried out at $T = 1.5$ K.

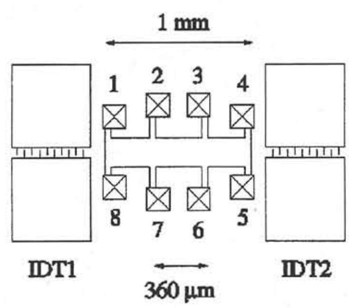

Fig. 1 Schematic of device geometry. The width of the mesa that hosts the asymmetric quantum wells is 200 µm. The aperture of the split-finger interdigital transducers is 60 µm. The mesa has eight Ohmic contacts, which are numbered as indicated.

3. Results and Discussion

Figure 2(a) shows a typical magnetic field dependence of the transmitted SAW amplitude. Here, the second subband is unoccupied by electrons. The filling factor ν indicates the number of Landau levels below the Fermi level, including the factor 2 due to spin degeneracy. (In our devices, spin splitting is not resolved at the measurement temperature.) In high magnetic fields, σ_{xx} of the 2DEG approaches zero at the quantum Hall states, resulting in the reduced SAW amplitude when ν is around even integers. The emergence of the double-dip structure implies that σ_{xx} fell below σ_m. It is, therefore, indicated that the maximum attenuation amplitude in our devices is ~ 0.6 dB.

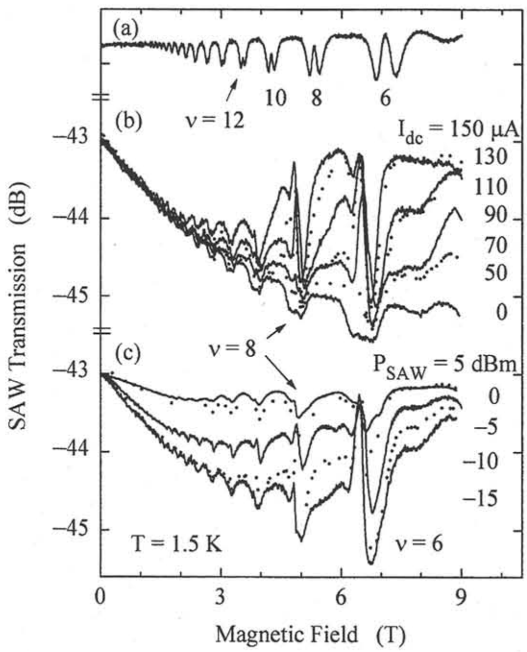

Fig. 2 (a) Transmission amplitude of the SAWs when only the ground-state subband is occupied by electrons. For (b) and (c), the Fermi level is just above the excited-state subband level. (b) Dependence on the dc current I_{dc} that flows between leads 1 and 4 when P_{SAW} = −15 dBm. (c) Dependence on the SAW power P_{SAW} when I_{dc} = 90 μA. Landau level filling factor ν is indicated for some quantum Hall states.

When the electron density is just above the occupation threshold of the excited-state subband, the SAW transmission exhibits an overall suppression with the magnitude of several dB in high magnetic fields, Figs. 2(b) and 2(c). In this circumstance of the background suppression, the SAW transmission develops gigantic structures when a dc current I_{dc} is injected into the device,[6] as shown in Fig. 2(b). An abrupt change of the SAW amplitude occurs at the middle of the double-dip structure, i.e., whenever the Fermi level crosses the Landau gap. Comparing with the SAW transmission curve when I_{dc} = 0, it is apparent that the magnitude of the modulation by far exceeds the prediction by Eq. (1).

It is not surprising that Eq. (1) is inapplicable for the two-layer system. The screening by the 2DEG determines the depth profiles of the electric fields generated by the SAWs. The SAW attenuation hence depends on the distance between the two conductive layers. In contrast, σ_{xx} is independent of the layer separation. Therefore, Eq. (1) is invalid if the partial screening of the electric fields when σ_{xx} is comparable with σ_m imposes electrostatic boundary conditions which are unusual in the single-layer counterpart.

Notice that the background SAW amplitude for large currents saturates at a value that is nearly identical with the SAW amplitude at zero magnetic field. We attribute the background suppression to the SAW attenuation by the excited-state subband. The drastic variation of the SAW amplitude at the integer filling factors is probably associated with the relocation of electrons between the two layers.

The SAW-generated electric fields are easily screened out by the 2DEG at zero magnetic field. However, the electric fields are large enough even to influence the charge transport in the quantum Hall regime when σ_{xx} is nearly zero.[2,7] As shown in Fig. 2(c), the giant SAW transmission modulation is very sensitive to the SAW power P_{SAW}. The smaller background suppression for larger P_{SAW} is ascribed to the increase of σ_{xx} of the second subband due to heating.

4. Conclusion

The SAW attenuation in an asymmetric two-layer system can be far greater than that in a single-layer system. Abrupt and gigantic modulations in the SAW transmission are made possible when a dc current is injected into a quantum Hall system. The mechanism responsible for this phenomenon may open a way to obtain huge SAW amplitude modulations even in materials having small $K_{eff}^2/2$ and to control them systematically.

Acknowledgment

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