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Phonon-assisted tunneling in a superlattice in an applied magnetic field

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We have studied acoustic phonon-assisted tunneling in a weakly coupled GaAs/AlAs superlattice (SL) in a magnetic field. At zero magnetic field, the phonon-assisted tunnel current, δI, exhibits maximum at a particular value of the Stark splitting, Δ_{max}, which depends on the spectral distribution of the nonequilibrium phonons. Applying the field ($B \leq 7$ T) perpendicular to the SL growth direction, z, had no significant effect on the phonon-assisted tunneling current compared to $B=0$. However, in a magnetic field parallel to z, Δ_{max} is proportional to B and weakly dependent on the phonon spectrum. This behavior, which we explain in terms of the momentum selection rules for phonon-assisted transitions in a magnetically quantized electron system, suggests that phonon amplification in the SL can be tuned by the magnetic field.

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I. INTRODUCTION

Stimulated by the pioneering work of Esaki and Tsu,[1] extensive research on electron transport in superlattice (SL) and multiple quantum well (MQW) structures has resulted in considerable theoretical and experimental progress.[2] The artificial periodicity of the SL leads to the splitting of conduction band into minibands and minigaps. An electric field, F applied parallel to growth axis, z, of the SL misaligns the energy levels in the adjacent quantum wells (QW) by $\Delta = eFD$, where D is the SL period, resulting in the formation of Wannier-Stark ladder states.[3] In a weakly coupled SL, if $\Delta \gg \Delta_m$ (Δ_m is the miniband width), the wave functions become localized in the QWs and the conduction will be due to hopping or tunneling of electrons between adjacent QWs.[4] The tunneling can occur either by an elastic process involving impurity or disorder scattering with the subsequent emission of phonons or by inelastic direct phonon-assisted tunneling.

Cavill *et al.*[5] studied the acoustic phonon-assisted tunneling in a GaAs/AlAs SL. An incident nonequilibrium phonon pulse generated by a metal film heater gave rise to an increase in tunnel current, δI, due to phonon-assisted tunneling of electrons between adjacent QWs. A maximum in δI was observed at a particular value of the Stark splitting, Δ_{max}, and the value of Δ_{max} was found to vary linearly with the temperature of the heater. A heated metal film emits an approximately black-body spectrum of phonons with a peak at $\nu_m = 2.8 k_B T_h / h$, where T_h is the heater temperature, which can be controlled by varying the power dissipated in the heater. Therefore, the linear dependence of Δ_{max} on T_h indicated that the SL was working as a frequency-tuneable phonon detector. The SL-tuneable phonon detector has subsequently been used to study the phonons generated by optical excitation of GaAs.[6] It was later shown by Kini *et al.*[7] that the measured dependence of δI on the Stark splitting was consistent with phonon amplification by stimulated emission occurring in the SL and the structure could form the basis of an electrically pumped terahertz saser device.[8]

A magnetic field B applied parallel to z quantizes the electron in-plane motion into Landau levels centered on energies $(N+\frac{1}{2})\hbar\omega_c$, where $\omega_c = eB/m^*$ is the cyclotron frequency and m^* is the effective electron mass. Application of a magnetic field in this direction has been shown to quench the current in a SL.[9] This has been attributed to elastic processes and/or quasielastic scattering by acoustic phonons in a Landau level. If a magnetic field is applied perpendicular to z, i.e., parallel to the layers of the SL, then there is an additional magnetic-field-induced localization of the electrons, which becomes significant if the quantum magnetic length $l_B = (\hbar/eB)^{1/2}$ becomes less than the localization length due to the electric field ($l_E = \Delta_m / eF$). Alexandrou *et al.*[10,11] have observed the splitting of minibands into Landau levels and the competition between the magnetic-field-induced and electric-field-induced localizations in GaAs/AlGaAs SLs in photocurrent experiments. In this paper, we present our experimental results on the effect of a magnetic field on the phonon-assisted tunneling current in a GaAs/AlAs SL. Our measurements show that applying a magnetic field in a direction parallel to the SL growth direction leads to an increase in the maximum energy of phonons that can cause phonon-assisted transitions between neighboring quantum wells. This indicates that applying a magnetic field could provide a means to increase the frequency of the phonons amplified by the SL. We also show that applying a magnetic field of up to 7 T parallel to the layers of the SL has no effect on the phonon-assisted tunneling current.

II. EXPERIMENTS

The experiments were performed using a 50-period GaAs/AlAs SL, each period consisting of 5.9 nm GaAs and 3.9 nm AlAs layers uniformly doped with Si to a density of 2×10^{22} m^{-3}. Calculation using the Kronig-Penney model gives a lowest miniband width of about 0.64 meV, while the second miniband lies at 280 meV above the first and is thus unlikely to be populated with electrons. The SL was separated from the n^+ (2×10^{24} m^{-3}) contact layers by 20 nm GaAs buffer layers. A 50 μm diameter device mesa was formed by etching and contacts with the emitter and collector layers made using GeAuNiAu, alloyed at 360 °C. The back surface of the substrate was polished and a 100-nm-thick film of CuNi was deposited.

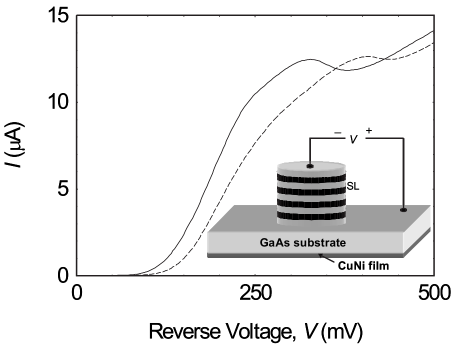

FIG. 1. *I-V* characteristics of the device in zero magnetic field (solid line) and at 4 T (dotted line) applied parallel to the electric field. Schematic representation of the experimental arrangement is shown in the inset.

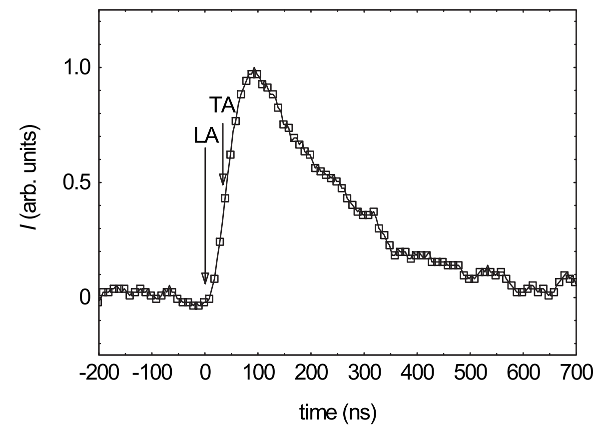

FIG. 2. A typical time-resolved phonon signal. The arrows indicate the arrival time of LA and TA phonons.

All measurements were performed with the sample at $T = 1.5$ K in an optical access helium cryostat. Pulses of nonequilibrium phonons were generated by heating the metal film with 10 ns pulses from a Q-switched Nd:YAG laser ($\lambda = 532$ nm) focused to a 30 μm diameter spot opposite to the SL detector. The intensity of the laser beam was varied by using calibrated neutral density filters. Using this arrangement, phonon source temperatures, T_h, in the range of 8–19 K could be achieved. The generated phonons propagated ballistically across the substrate and on reaching the detector gave rise to a change in tunnel current, δI, which was amplified using a high-speed preamplifier with a gain of $\times 10$ and an input impedance of 1 kΩ. The cryogenic wiring between the device and preamplifier had a capacitance of ~ 100 pF, giving a system rise time of ~ 100 ns. For pulses of 10 ns duration, this introduces a signal loss of about one order of magnitude, which was made up by further stages of amplification before the signal was fed to an acquisition system consisting of a fast digitizer and signal averager. The cryostat houses a superconducting magnet, capable of providing a magnetic field of up to 7 T parallel to the axis of the optical window.

III. RESULTS AND DISCUSSION

Figure 1 shows the current-voltage (*I-V*) characteristics of the device in zero magnetic field. The device turns on at the threshold bias voltage, $V_T \approx 75$ mV, which is probably the bias required to align the Fermi energy of the emitter and the nearest well. After that, the current increases monotonically for biases up to about 250 mV. Fluctuations of the current with applied bias above 250 mV indicate the formation and growth of static electric field domains within the sample.[12] At the first current peak (~ 250 mV), the system switches from a single domain of constant field throughout the SL to two or more domains of significantly different field strength separated by a domain boundary which contains space charge to provide the field gradient. The peak is followed by a fall as the high-field domain expands at the expense of the low-field domain. As the bias is increased further, the process is repeated leading to a series of peaks in *I-V*. All the measurements described here were made at bias voltages between V_T and 250 mV, where the variation in the electric field along the structure is assumed to be uniform. In this case the energy drop per period of the SL is reasonably assumed to be given by $\Delta = \gamma e (V - V_T)/50$, where γ is the fraction of the applied voltage that is dropped across the SL excluding the contacts and spacer layers. The *I-V* characteristics at $B = 4$ T applied parallel to z are also shown in Fig. 1. Quenching of the current is observed as in previous work.[9] Fig. 2 shows a typical time-resolved phonon signal $\delta I(t)$. The calculated arrival times of the longitudinal acoustic (LA) and transverse acoustic (TA) phonons are marked. To obtain the δI-vs-Δ curves shown in Figs. 3 and 4, $\delta I(t)$ was integrated over a time window between the LA and TA arrival.

Figure 3 shows δI-vs-Δ curves for different heater temperatures with zero magnetic field. In the absence of any magnetic field, Δ_{max} varies linearly with T_h as shown in the inset of Fig. 3. We may write, $\Delta_{max} = \Delta_0 + \alpha(2.8 k_B T_h)$, and, using a least-squares fit to the experimental data, we obtain $\alpha = 0.065$ and $\Delta_0 = 1.12$ meV. This shows that the device may be used as a tuneable phonon spectrometer as discussed previously.[5] In the present paper we focus on the effect of a magnetic field on the phonon-assisted tunneling current.

Figure 4 shows the δI-vs-Δ curves with magnetic fields of $B = 1$, 2, 4, and 7 T applied parallel to the growth axis. It can be seen that for $B \geq 2$ T, Δ_{max} is only weakly dependent on

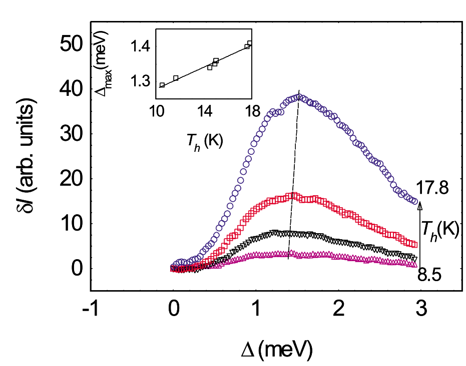

FIG. 3. (Color online) δI-vs-Δ curves for temperatures between 8.5 and 17.8 K with no magnetic field applied. The dotted line is guidance for the eyes. Inset shows Δ_{max} as a function of the T_h. The solid line is a least-squares fit to the data.

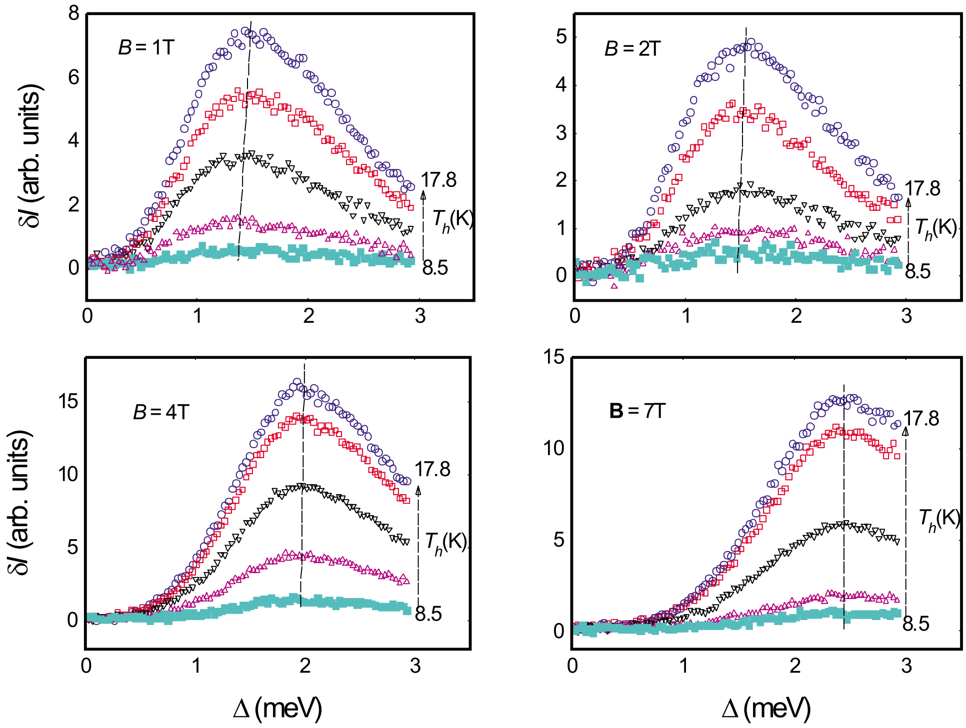

FIG. 4. (Color online) δI-vs-Δ curves with various magnetic fields applied parallel to the SL growth direction, z.

T_h and that the value of Δ_{max} increases with applied magnetic field strength, reaching $\sim$2.5 meV at 7 T, compared to $\sim$1.5 meV at zero magnetic field. The observed shape of the δI-vs-Δ curves is in good agreement with theoretical predictions assuming that stimulated emission of phonons is the dominant mechanism of phonon-assisted vertical transport in the SL.[7,13] It has been shown that this can lead to a phonon instability and amplification for particular modes determined by the selection rules for the electron-phonon interactions.[14] Detailed numerical calculations of δI as a function of Δ in zero magnetic field were presented in Ref. 7. To understand the effect of the magnetic field applied parallel to z, we consider semiquantitatively the energy and momentum conservation conditions for the stimulated emission processes in zero and applied magnetic fields.

Considering first the case of zero applied magnetic field: the transitions between two neighboring wells are shown schematically in Fig. 5. To conserve energy, the energy of the phonon emitted when an electron makes a transition, $\hbar\omega = \hbar q c_s \leq \Delta$, where q is the phonon wave-vector magnitude and c_s is the speed of longitudinal sound in the SL (5000 ms^{-1}). There is also a requirement that the in-plane and z components of momentum, $\hbar q_{\|}$ and $\hbar q_z$, respectively, are conserved. The only requirement for the z component is that its value is within the bounds of uncertainty associated with the z confinement of electrons in the quantum wells.

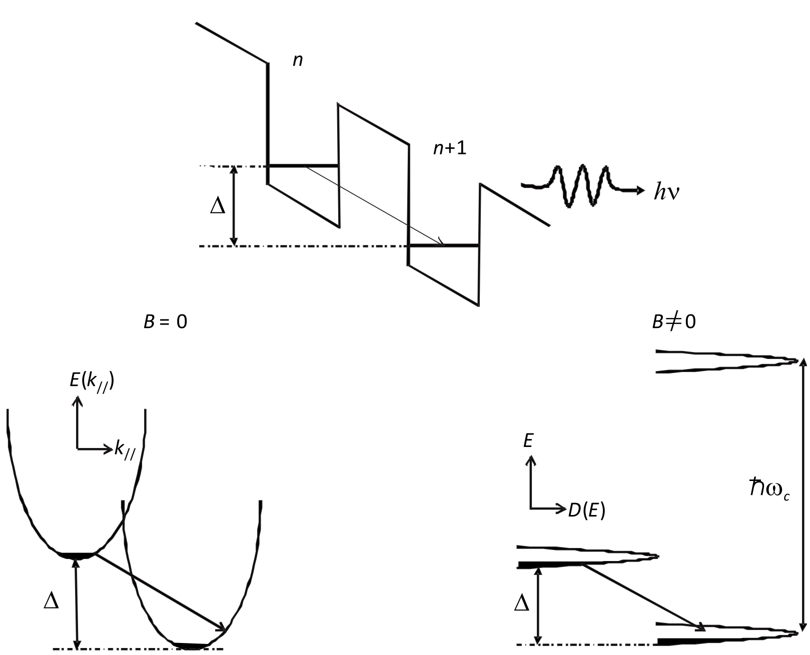

FIG. 5. Schematic showing possible phonon-assisted electronic transitions between neighboring QWs in an SL, and in zero and applied magnetic fields. In zero field, the 2D electron dispersion is shown with occupied states, which are indicated by the filled-in areas. In nonzero field the 2D DOS is split into Landau levels separated in energy by $\hbar\omega_c$.

This effectively places a cutoff on the maximum value of the z component of phonon wave vector of $q_z(\max)=2\pi/w$, where w is the quantum well width.[15] For our SL, $w=5.9$ nm, so $q_z(\max)=11\times10^{8}$ m^{-1}, which corresponds to a maximum energy (for a phonon propagating near parallel to z) of $\hbar q_z(\max)c_s=3.5$ meV. Because this is significantly larger than the values of $\Delta_{\max}$ measured in the experiment, we can conclude that the q_z cutoff does not play a part in determining the dependence of δI on Δ. The in-plane momentum conservation requires, $q_\parallel=q\sin(\theta)$, where q is the magnitude of the phonon wave vector and θ is the angle between the phonon wave vector and z. In zero magnetic field, $q_\parallel$ can take any value up to a cutoff at $2k_{\rm F}+k_\Delta$, where k_F is the Fermi wave vector and $k_\Delta=\sqrt{\frac{2m^*}{\hbar^2}}(\sqrt{E_F+\Delta}-\sqrt{E_F})$, (see Fig. 5). In this case, for $E_{\rm F}$ (~0.1 meV) $\ll\Delta$, we obtain $q_\parallel(\max)\approx\sqrt{\frac{2m^*\Delta}{\hbar^2}}$. In the experimental geometry the average value of θ is about 6 degrees and, for a phonon incident at this angle, the cutoff is at $\hbar\omega(\max)=\frac{c_s}{\sin\theta}\sqrt{2m^*\Delta}\approx10^{11}\sqrt{\Delta}$ meV. The important point to note here is that, for $\Delta>1.8$ meV, the cut-off energy is lower than Δ and so the in-plane momentum conservation condition cannot be ignored.

We now move on to consider the case of a magnetic field applied parallel to z: based on the typical electron mobility, we can estimate the electron scattering time, τ, in the QWs at approximately 5×10^{-13} s which means that the condition for magnetic quantization, $\omega_c\tau>1$, is satisfied at fields above about 2 T. At such magnetic field strengths, the Landau level separation $\hbar\omega_c$ is greater than the value of the Stark splitting at the largest applied bias used in the experiments. Therefore, at the electron density in the QWs ($\sim10^{14}$ m^{-2}), only the lowest ($N=0$) Landau level is part occupied and the electron transitions between neighboring quantum wells all take place within that level. Owing to the sharply peaked nature of the density of states (DOS) in a magnetically quantized 2D electron system, in order to conserve energy, the energy of the phonons emitted when an electron hops between neighboring quantum wells is equal to the Stark splitting ($\pm$ the Landau level width) at all values of applied magnetic field (>2 T). The magnetic field further quantizes the transverse motion and the in-plane momentum conservation condition now becomes, $q_\parallel(\max)=1/l_B$,[15] where $l_B\approx26/B^{1/2}$ nm. So, for a particular value of the magnetic field, there will be a maximum value of Δ at which transitions can occur, this is given approximately by $\frac{\hbar c_s\sqrt{B}}{26\times10^{-9}\sin(\theta)}$. This is about 2 meV at 4 T, which corresponds closely to the experimentally observed peak at $\Delta_{\max}=1.9$ meV. Therefore, due to in-plane momentum conservation, $\Delta_{\max}$ is expected to increase as $B^{1/2}$ for fields above about 2 T and, as shown in Fig. 6, the experimental data is in reasonable agreement with this prediction.

At even the lowest value of T_h used, the peak in the Planckian phonon spectrum is above 2 meV, which explains the weak dependence of $\Delta_{\max}$ on T_h. At all T_h there are nonequilibrium phonons present in the source spectrum, which satisfy the selection rules for phonon-assisted interwell transitions and, due to the process of stimulated emission, the occupation number of these modes is increased.[7] Therefore, we believe, by changing the applied magnetic field it is possible to tune the phonon frequencies that are amplified in the SL. However, more rigorous theoretical modeling is needed to give a full quantitative account for the shape of the δI-vs-Δ curves in a magnetic field.

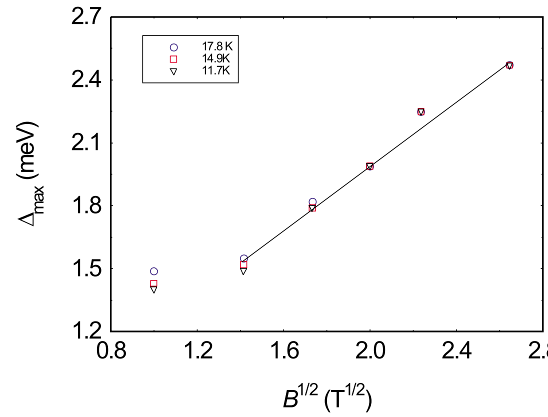

FIG. 6. (Color online) Value of Stark splitting at which the peak in δI occurs, $\Delta_{\max}$, as a function of the square root of the applied magnetic field strength for different temperatures; note the linear dependence above $B=2$ T for which $\omega_{\rm c}\tau>1$.

We have also measured the phonon-assisted tunneling in the SL in crossed electric and magnetic fields, when the magnetic field is applied perpendicular to z. The δI-vs-Δ curves shown in Fig. 7 are very similar to the $B=0$ measurements, except for a slight increase in the value of $\Delta_{\max}$. In this configuration Landau levels are not formed and, even at the highest magnetic fields used ($B=5$ T) the magnetic length ($l_{\rm B}=11$ nm) is larger than the localization length due to the electric field $l_{\rm E}=\Delta_{\rm m}/eF\approx3$ nm at $(V-V_{\rm T})=100$ mV. Therefore, we would not expect to see a significant effect on the behavior of the device due to the magnetic field applied parallel to the layers.

IV. CONCLUSIONS

Our measurements have shown that applying a magnetic field in a direction parallel to the SL growth direction leads to an increase in the maximum energy of phonons that can cause phonon-assisted transitions between neighboring quantum wells. We account for this observation in terms of the

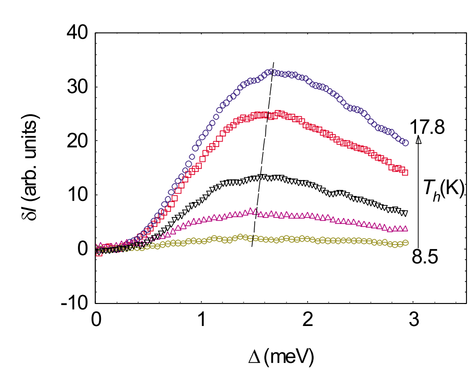

FIG. 7. (Color online) δI-vs-Δ curves with a magnetic field of 5 T applied parallel to the SL layers.

increase in the cut-off energy due to conservation of momentum in the plane of the wells as the field strength is increased. Such a SL has previously been shown to amplify phonons, and this paper indicates that applying a magnetic field could provide a means to increase the frequency of the phonons amplified by the SL. Applying a magnetic field of up to 7 T parallel to the layers of the SL has been shown to have no effect on the phonon-assisted tunneling current and the SL.

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