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Tunneling spectroscopy of GaAs/$Al_xGa_{1-x}As$/GaAs single-barrier heterojunction diodes

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We investigate the effect of the electron-phonon interaction during the tunneling process in GaAs/$Al_xGa_{1-x}As$/GaAs heterojunction tunneling structures by measuring the first (dI/dV) and the second (d^2I/dV^2) derivative spectra of tunneling current at 4.2 K. We observe cusplike conductance decreases rather than conductance increases in both bias polarities near the energies of optical phonons in GaAs and $Al_xGa_{1-x}As$. These conductance decreases arise from the electronic self-energy effect in the n-type GaAs electrodes. By comparing the signal positions with phonon modes, it is found that in the vicinity of the electrode-barrier interface the electronic dispersion in the GaAs electrodes is strongly modified by the interaction not only with longitudinal optical phonons in the GaAs electrodes but also with the interface phonons at the electrode-barrier interfaces. This is clear evidence that electron–interface-phonon interaction is important in the transport properties of semiconductor heterojunctions.

The GaAs/$Al_xGa_{1-x}As$/GaAs single-barrier heterojunction diode is one of the ideal materials to study the basic physics in the tunneling process. Furthermore, it has become very important technologically, since it has been used as an electron emitter for hot-electron transistors (HET's).[1,2] Although several studies on the electrical properties in this structure have been reported so far,[3–6] the effect of the electron-phonon interaction during the tunneling process has not been clarified yet.[7]

In this work, we investigate the effect of the electron-phonon interaction on the tunneling current by measuring the first (dI/dV) and the second (d^2I/dV^2) derivative spectra of tunneling current systematically. Although it has been widely anticipated that the phonon-assisted process in the $Al_xGa_{1-x}As$ barrier gives rise to a step *increase* in conductance at the threshold bias voltage for the phonon emission, we observed, on the contrary, cusplike *decreases* in conductance in both bias polarities, which arises from the electron-phonon interaction in the electrodes. By comparing the signal positions with phonon modes, it is clarified that in the vicinity of the electrode-barrier interface the electronic dispersion in the GaAs electrodes is strongly modified by the interaction not only with the GaAs electrode optical phonons but also with the interface mode phonons at the electrode-barrier interfaces. This is a clear demonstration of the importance of the electron–interface-phonon interaction in semiconductor heterojunction systems.

The samples used in the present study were grown on Si-doped n^+-GaAs substrates by molecular-beam epitaxy (MBE). The GaAs/$Al_xGa_{1-x}As$/GaAs single-barrier heterojunction diode structures were prepared by growing successively a 6500-Å–thick Si-doped GaAs buffer layer, a 20-Å–thick undoped GaAs setback layer, a 75-Å–thick undoped $Al_xGa_{1-x}As$ barrier layer, a 20-Å–thick undoped GaAs setback layer, and a 4000-Å–thick Si-doped GaAs cap layer. The growth was interrupted for 1 min at each interface to smooth out interface roughness.[8] The growth rates and the alloy compositions x in the $Al_xGa_{1-x}As$ were calibrated by the reflection high-energy electron diffraction (RHEED) oscillation effect. The alloy compositions x were adjusted to be 0.50 and 0.70. The doping density in the n^+-GaAs electrodes is 1.2×10^{18} cm^{-3}; the equivalent Fermi energy in the GaAs electrode is about 60 meV. The diode pattern with an area of 20×20 μm^2 was defined by He$^+$ ion bombardment or mesa etching. The Ohmic contacts were made by alloying AuGe at 400 °C in Ar ambient.

I-V, dI/dV, and d^2I/dV^2 spectra of tunneling current were measured systematically at 4.2 K. dI/dV spectra were taken by applying a 532-Hz current source with a modulation amplitude of 0.1 μA. Second derivative spectra were taken using a second-harmonic detection system,[9] which was operated at a fundamental frequency of 532 Hz with typical modulation voltage of 1 mV.

Figure 1 shows a typical conductance (G or dI/dV) spectrum measured on GaAs/$Al_{0.5}Ga_{0.5}As$/GaAs diodes at 4.2 K. Here, V refers to the voltage applied on the top electrode (surface side). The conductance spectrum is almost symmetrical with respect to bias polarity, except for the fact that the bias voltage where the conductance becomes minimum is slightly shifted toward the negative region by about 5 mV. Although the origin of this small

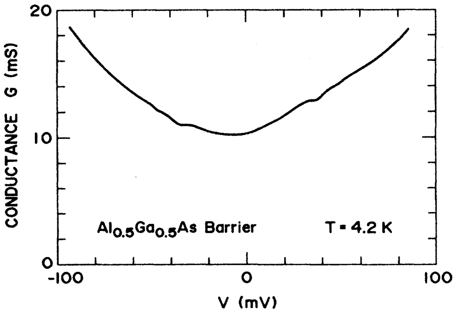


FIG. 1. Junction conductance G of a GaAs/$Al_{0.5}Ga_{0.5}As$/GaAs diode measured at 4.2 K is plotted as a function of bias voltage.

asymmetry is not clear at present, a possible mechanism is the slight difference in the conduction-band discontinuity at the two electrode-barrier interfaces, which is caused by the transient effect of Al beam flux during MBE growth; AlAs mole fraction at the bottom interface is slightly higher than that at the top interface. When we look at the conductance spectrum more closely, we will notice decreases in conductance in both bias polarities at around ± 35 and ± 50 mV. It should be noted that these structures are contrary to the phonon-assisted tunneling structure,[10] which consists of a step increase in conductance in both bias polarities.

In order to resolve detailed features and to determine the bias positions of the phonon-induced signals, we measured the second derivatives (d^2I/dV^2) of the tunneling current on these diodes. Figure 2 shows a typical d^2I/dV^2 spectrum measured on GaAs/Al$_{0.5}$Ga$_{0.5}$As/GaAs diodes at 4.2 K. The observed spectra are essentially the same as that shown in Fig. 1 of Ref. 7, except for the fact that the small peak which is labeled (b) in Ref. 7 is absent in our case. Superposed on a slowly varying curve, four antisymmetric structures are clearly resolved at around ± 35 and ± 50 mV, which are close to the energies of the longitudinal optical (LO) phonons in GaAs and the AlAs-like LO phonons in Al$_x$Ga$_{1-x}$As alloy, respectively. Detailed discussion on the phonon modes will be made later. The small structures observed at around zero bias did not show significant temperature dependence below 4.2 K and may be associated with tunneling via impurity states in the Al$_x$Ga$_{1-x}$As.[11]

The electron-phonon interaction in a many-body system is often described by an electron self-energy Σ, which is a complex quantity.[12,13] Appelbaum and Brinkman[12] and Caroli *et al.*[13] theoretically predicted that, if the electron-phonon interaction occurs in the electrode, ImΣ gives rise to a *step decrease* in conductance at the phonon energy, which is even with respect to the bias polarity. The electron-phonon interaction in the barrier always gives rise to a *step increase* in conductance (phonon-assisted process). On the other hand, the contribution from ReΣ, which arises from the electron-phonon interaction in the electrode, modifies the electronic dispersion and gives rise to a broad dispersive *cusplike* structure in conductance. The symmetry of this structure with respect to bias polarity depends on the detail of the form of the interaction matrix element.[14,15] Since the samples used in the present study have a symmetric structure of GaAs/Al$_x$Ga$_{1-x}$As/GaAs, only the symmetric spectra of the phonon-induced structures can be obtained.

In order to get further information on this phonon structure, we decomposed the tunneling conductance ($G \equiv dI/dV$) into an even part, $G^e(V) \equiv \frac{1}{2}[G(+V)+G(-V)]/G(0)$, and an odd part, $G^o(V) \equiv \frac{1}{2}[G(+V)-G(-V)]/G(0)$, following the method by Rowell, McMillan, and Feldmann[16] and Tsui.[17] Figures 3(a) and 3(b) show typical $G^e(V)$ and $G^o(V)$ characteristics of GaAs/Al$_{0.5}$Ga$_{0.5}$As/GaAs diodes, respectively. It is apparent from the result of Fig. 3(a) that the phonon structures can indeed be described as *broad cusplike decreases* in conductance in both bias polarities. The conductance decrease at ± 36 mV is about 0.4 mS and that at ± 47 mV is about 0.1 mS. However, the conductance increase due to the phonon-assisted process is negligibly small. This fact suggests that the effect of the electron-phonon interaction in the barrier is small. Appelbaum and Brinkman[12] predicted that the phonon-assisted process becomes appreciable only when $E_F/E_B > 0.2$. Here, E_F is the Fermi energy in the electrodes and E_B is the barrier height. Since E_F/E_B is about 0.1 in our case, the absence of the phonon-assisted signal is reasonable. On the other hand, the odd part of conductance $G^o(V)$, as shown in Fig. 3(b), is dominated by the asymmetry of the background conductance, and the phonon-induced structures could not be resolved.

It should be noted from the discussions above that the decreases in conductance at approximately ± 36 mV and even those at approximately ± 47 mV are due to the

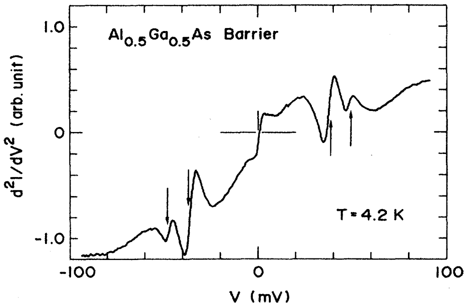
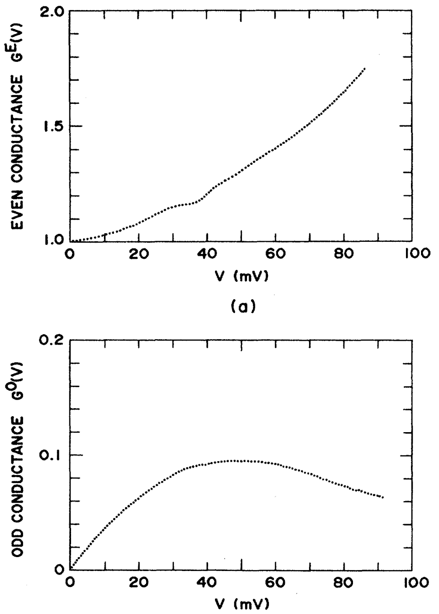


FIG. 2. Bias dependence of the second derivative spectrum (d^2I/dV^2) of the tunneling current in a GaAs/Al$_{0.5}$Ga$_{0.5}$As/GaAs diode measured at 4.2 K. Arrows indicate the bias positions where the slope of the d^2I/dV^2 curve becomes maximum.



(a)

(b)

FIG. 3. Bias dependence of the normalized junction conductance of a GaAs/Al$_{0.5}$Ga$_{0.5}$As/GaAs diode measured at 4.2 K; (a) the even part and (b) the odd part of the conductance.

change in the electronic dispersion which is induced by the electron-phonon interaction *in the electrode,* although the electrodes are pure GaAs. In order to clarify the phonon modes which interact with electrons during the tunneling process, we plot in Fig. 4 the observed signal positions eV (e: elementary charge) of Fig. 2 as functions of AlAs mole fraction in the Al$_x$Ga$_{1-x}$As barrier.[18] The energies are identified with bias values at points of maximum slope in the d^2I/dV^2 curves, corresponding to the center of cusplike structures in the conductance. The results for GaAs/Al$_{0.7}$Ga$_{0.3}$As/GaAs diodes are also plotted in the figure. LO (ω_{L1} and ω_{L2}) and transverse optical (TO; ω_{T1} and ω_{T2}) phonon energies at the Γ point[19,20] are shown by solid lines. From the figure, it is noticed that there are two branches of phonon-induced signals in the conductance spectra. The observed phonon energies in the lower branch are almost independent of the AlAs mole fraction x in the barrier and are about 36 meV, which is very close to the LO phonon energy (36.2 meV) in GaAs. This fact indicates that this phonon-induced signal originates from the interaction between the electrons and the GaAs electrode LO phonons. On the other hand, the observed phonon energies in the upper branch depend on x and are somewhat lower than the AlAs-like LO phonon (ω_{L1}) energies expected in the Al$_x$Ga$_{1-x}$As alloy barrier.

In order to understand these experimental results, we have to take into account the fact that the phonon modes are strongly modified by the heterojunction boundary effect. In GaAs/Al$_x$Ga$_{1-x}$As heterojunction systems, optical phonon modes are strongly confined into an individual layer due to the large difference in the mechanical properties of Ga and Al atoms.[21] The amplitudes of these confined phonons vanish at the heterointerface. However, there is another mode, namely the interface mode, the electrostatic potential of which has maximum amplitude at the interface and penetrates into the adjacent material exponentially as $\exp(-qz)$, where q is the phonon wave vector parallel to the interface and z is the distance measured from the electrode-barrier interface.[22]

Caroli *et al.*[13] predicted that due to the destructive interference effect in the many-body effect, the major contribution to the phonon structure comes from the electron-phonon interaction within a distance of a Fermi wavelength λ_F from the barrier, and that interactions which occur deep inside the electrode have no observable effect. Since the interface mode phonon with $q=2\pi/\lambda_F$ penetrates into the electrode over a distance of $\sim\lambda_F$, the interface mode phonons can play a significant role in electron-phonon interaction during the tunneling process.

We calculated the interface phonon modes using the dielectric continuum model.[23,24] The shaded regions are the allowed bands for the interface modes. The dashed lines (ω_1, ω_2, and ω_3) correspond to the phonon energies when $qd \gg 1$, with d the barrier thickness. The phonon-induced signals observed around 47 meV are in between the ω_{L1} mode and the ω_1 mode. This fact strongly indicates that during the tunneling process the electrons interact with the interface mode phonons whose amplitude decreases away from the interface and whose polarization field parallel to the interfaces is symmetric with respect to the center of the barrier (ω_{S1} mode). We should add a point that, although six interface modes are expected for the alloy barrier case, only the ω_{S1} mode was detected. This is probably because this mode has the largest Frohlich coupling constant among the six interface modes.[25]

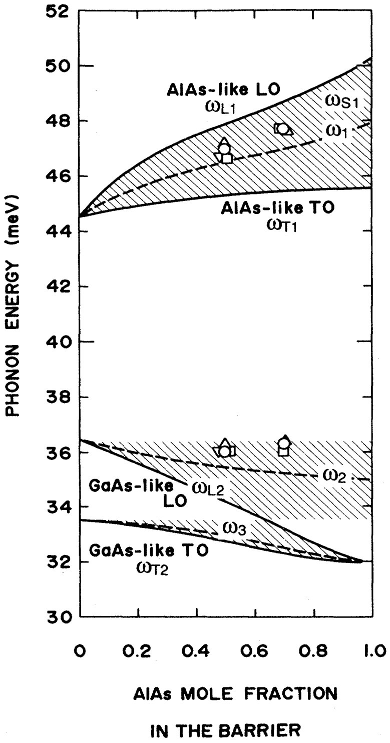


FIG. 4. The measured phonon energies are plotted by symbols as functions of AlAs mole fraction in the barrier. In this figure, LO (ω_{L1},ω_{L2}) and TO (ω_{T1},ω_{T2}) phonon energies expected in the bulk alloy are also plotted by solid lines. The shaded regions are the allowed bands for interface mode phonons. The dashed lines (ω_1, ω_2, and ω_3) correspond to the interface phonon energies for the short-wavelength limit. The definition of the ω_{S1} interface mode is given in the text.

The above considerations suggest that heterojunction tunneling experiments are very suitable for observing the electron–interface-phonon interaction, since tunneling probability is determined within a Fermi wavelength ($\sim$100 Å) from the electrode-barrier interface. However, the transport experiments of two-dimensional (2D) electrons are not suitable, because the wave functions of the 2D electrons vanish at the interfaces.

In summary, we investigate the effect of the electron-phonon interaction during the tunneling process in GaAs/Al$_x$Ga$_{1-x}$As/GaAs heterojunction tunneling structures by measuring the first (dI/dV) and the second (d^2I/dV^2) derivative spectra of tunneling current at 4.2 K. We observe cusplike conductance decreases rather than conductance increases in both bias polarities near the energies of the optical phonons in GaAs and Al$_x$Ga$_{1-x}$As. These conductance decreases arise from the electronic self-energy effect in the n-type GaAs electrodes. By comparing the signal positions with phonon modes, it is found that in the vicinity of the electrode-barrier interface the electronic dispersion in the GaAs electrodes is strongly modified by the interaction, not only with LO phonons in the GaAs electrode, but also with interface phonons at the electrode-barrier interfaces. This is a clear demonstration that the electron-interface phonon interaction is important in the transport properties of semiconductor heterojunctions.

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