Sequential Single-Phonon Emission in GaAs-Al$_x$Ga$_{1-x}$As Tunnel Junctions

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Periodic structure is observed in the tunneling current from heavily doped (n^+) GaAs through Al$_x$Ga$_{1-x}$As into lightly doped (n^-) GaAs at 1.6 K in magnetic fields large enough for magnetic freezeout of electrons to occur in the n^--GaAs. Sixteen periods are observed for $-0.6\ \text{V} < V_G < 0\ \text{V}$. The phase and the voltage periodicity, 0.036 V, are *independent* of magnetic field. The mechanism appears to involve LO-phonon emission events by ballistic electrons. This is the first observation of sequential single-phonon emission observed in electron transport.

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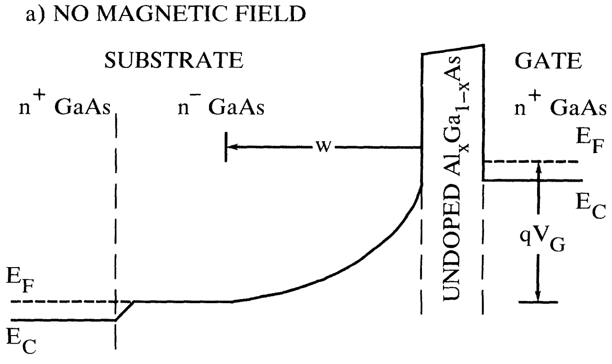
We have observed a remarkable periodic structure in the dc current-voltage (I-V) curves of n^--GaAs–undoped Al$_x$Ga$_{1-x}$As–n^+-GaAs capacitors at 1.6 K in the presence of high magnetic fields parallel to the direction of current flow. Current flow in the capacitor is due to direct electron tunneling from heavily doped (n^+) GaAs through Al$_x$Ga$_{1-x}$As into lightly doped (n^-) GaAs. The periodic structure is seen only for magnetic fields high enough ($B > 4$ T) that magnetic freezeout of carriers in the n^--GaAs occurs. However, contrary to the usual observations of magnetoconduction or magnetophonon effects in semiconductors,[1] neither the voltage spacing nor the phase of the observed oscillations depends on the magnitude of the magnetic field. The voltage periodicity is 0.036 V; sixteen periods have been observed for $-0.6\ \text{V} < V_G < 0$ V, where V_G is the voltage applied to n^+-GaAs. We attribute the structure to sequential emission of LO phonons in the n^--GaAs.

We have recently shown that undoped Al$_x$-Ga$_{1-x}$As is a nearly ideal dielectric in n^--GaAs–undoped Al$_x$Ga$_{1-x}$As–n^+-GaAs capacitors.[2] Capacitance-voltage (C-V) characteristics are closely fitted by the theory of ideal semiconductor-insulator-semiconductor (SIS) structures. For low voltages and for temperatures between 100 and 300 K, I-V characteristics are determined by thermionic emission over the barrier at the Al$_x$Ga$_{1-x}$As-GaAs interface. At low temperatures and higher voltages, tunneling is the dominant conduction mechanism; resonant Fowler-Nordheim tunneling is observed at 4.2 K in samples with Al$_x$Ga$_{1-x}$As thicknesses of 30–40 nm.[3] We now find that direct tunneling occurs in samples with Al$_x$Ga$_{1-x}$As thickness of ~ 20 nm.

The sample studied was grown by molecular-beam epitaxy and is shown schematically in Fig.


a) NO MAGNETIC FIELD

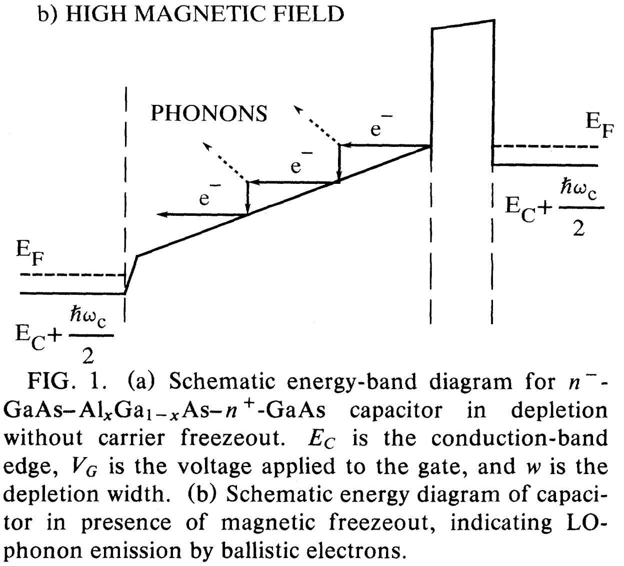

b) HIGH MAGNETIC FIELD

FIG. 1. (a) Schematic energy-band diagram for n^--GaAs–Al$_x$Ga$_{1-x}$As–n^+-GaAs capacitor in depletion without carrier freezeout. E_C is the conduction-band edge, V_G is the voltage applied to the gate, and w is the depletion width. (b) Schematic energy diagram of capacitor in presence of magnetic freezeout, indicating LO-phonon emission by ballistic electrons.

1(a). Sample preparation and procedures for measuring *C*-*V* and *I*-*V* curves have been described.[2] The n^--GaAs ($1.4\times10^{15}/\mathrm{cm}^3$) is $\sim 1\ \mu$m thick, the $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ ($x\sim 0.4$) layer is ~ 20 nm thick, and the n^+-GaAs ($1.5\times10^{18}/\mathrm{cm}^3$) which serves as a gate electrode for the capacitor is ~ 400 nm thick. The sample area is 4.13×10^{-4} cm^2. Data were taken digitally by computer-controlled instrumentation; data processing, including the taking of derivatives, was done by computer. Magnetic field measurements were made in a superconducting magnet with the sample immersed in pumped helium at 1.6 K.

Shallow hydrogenic impurities in semiconductors form a band at high enough concentrations, and have metallic conduction at low temperatures.[4] High magnetic fields can cause electrons to freeze out onto donors in the metallic conduction regime. Yafet, Keyes, and Adams[5] introduced the dimensionless parameter $\gamma=\hbar\omega_c/(2\ \mathrm{Ry})$ to characterize the magnetic field needed to observe magnetic freezeout. $\omega_c = qB/m^*$ is the cyclotron resonance frequency of an electron of effective mass m^* and charge q in a magnetic field B, and 1 Ry is the Rydberg energy of the hydrogenic impurity. Theory suggests that magnetic freezeout occurs when γ approaches 1, or $B\sim 2.35\times10^5(m^*/m\epsilon_s)^2$ T, where m is the free-electron mass and ϵ_s is the dielectric constant of the semiconductor. The minimum value of B for magnetic freezeout depends on concentration. For GaAs, with $m^*=0.067m$ and $\epsilon_s=12.8$, $\gamma=1$ for $B=6.4$ T. The radius of the cyclotron orbit at 6.4 T is ~ 10 nm, about the same as the effective Bohr radius in GaAs. The effect of magnetic field on conductivity and Hall effect has been used previously to study magnetic freezeout in GaAs.[6,7] Such measurements involve both carrier concentrations and carrier transport. We find that capacitance measurements also give information about freezeout.

Carrier concentration versus depth from the n^--GaAs–$\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ interface can be determined from *C*-*V* measurements of $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ capacitors in depletion. The method of determining concentration profiles is the same as used for metal-oxide-semiconductor (MOS) capacitors based on silicon,[8] with the $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ replacing the SiO_2 and GaAs replacing silicon. Conditions in our samples with regard to the interpretation of *C*-*V* curves differ from those found in conventional MOS capacitors. Quasiequilibrium in the substrate cannot be assumed in our case since sufficient electronic current flows by tunneling to force the quasi Fermi level for electrons to always be near $E_C+\hbar\omega_c/2$, where E_C is the conduction-band edge. Schematic band diagrams for measurement of capacitance at zero and high magnetic fields are shown in Figs. 1(a) and 1(b).

C-*V* curves for gate voltages corresponding to depletion and for different values of magnetic field are shown in Fig. 2(a). The full *C*-*V* curve at 0 T is similar to that in Fig. 4(a) of Ref. 3. The maximum experimental capacitance in accumulation is 123 pF. C_I, the capacitance due only to undoped $\mathrm{Al}_x\mathrm{Ga}_{1-x}$-As, is determined by modeling of *C*-*V* curves and is 205 pF. At 0 and 2 T, *C*-*V* curves are nearly identical. At 4 and 6 T, there is a pronounced decrease in capacitance which is attributed to magnetic freezeout of donors. At 10 T and above, the *C*-*V* curve is nearly flat; the n^--GaAs is completely

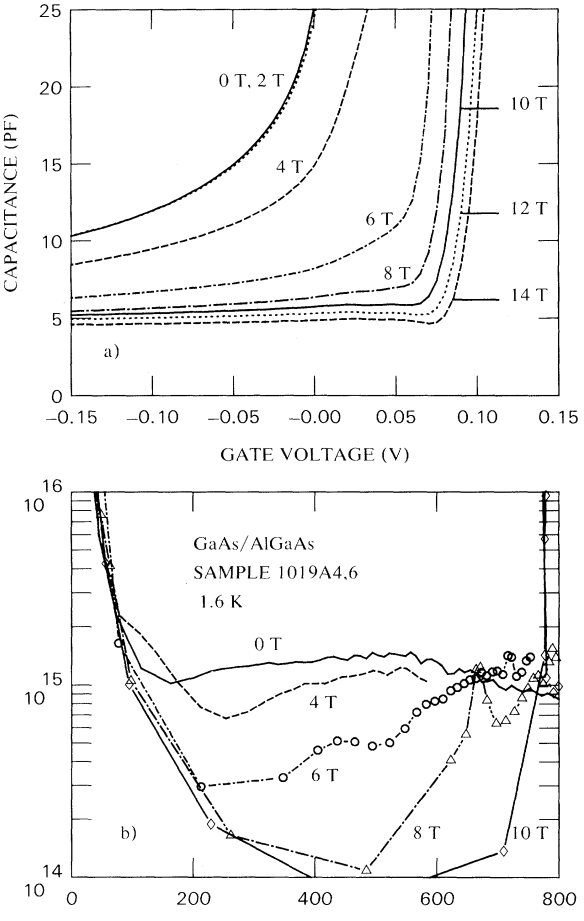


FIG. 2. (a) Capacitance-voltage curves in depletion for different magnetic fields. Frequency is 100 kHz. The insulator capacitance is 205 pF. (b) Carrier concentration profiles for different magnetic fields derived from capacitance-voltage curves.

frozen out and the value of capacitance corresponds to that expected for ~20 nm of $Al_xGa_{1-x}As$ in series with an insulating layer of GaAs that is ~1 μm thick. Carrier concentration profiles corresponding to the C-V curves are shown in Fig. 2(b). The depth is measured from the $Al_xGa_{1-x}As$-n^--GaAs interface. At 0 and 2 T, the average carrier concentration is $1.4\times10^{15}/cm^3$. This is the same value derived from C-V curves at 4.2 and 77 K. There is no thermal freezeout in the n^--GaAs. At 4 T, the average carrier concentration decreases to $1\times10^{15}/cm^3$. For higher fields, connected points are shown in the concentration profile since only a few points are calculated. The apparent rise in the carrier concentration above 500 nm in the 8 and 10 T curves is an artifact associated with the standard method that we use to derive the carrier concentration from the C-V curve.[8] It is related to the dip in the C-V curves at about 0.07 V. This dip may be a manifestation of the Gray-Brown effect.[9] Thus our data show that increasing magnetic field freezes electrons onto donors, converting ionized centers into neutral centers and reducing the ionized impurity concentration in the substrate layer. The n^--GaAs acts as an insulator of thickness ~1 μm.

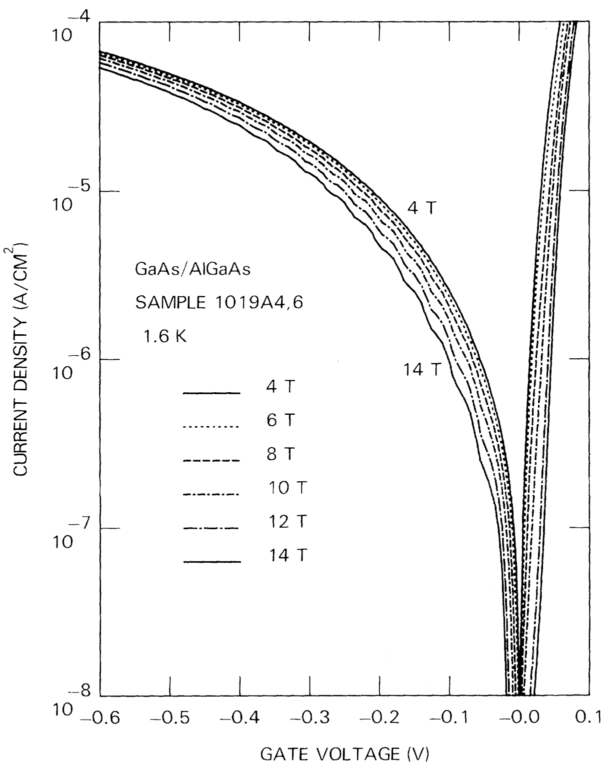


FIG. 3. Current density vs gate voltage for n^--GaAs-$Al_xGa_{1-x}As$-n^+-GaAs capacitor for different magnetic fields.

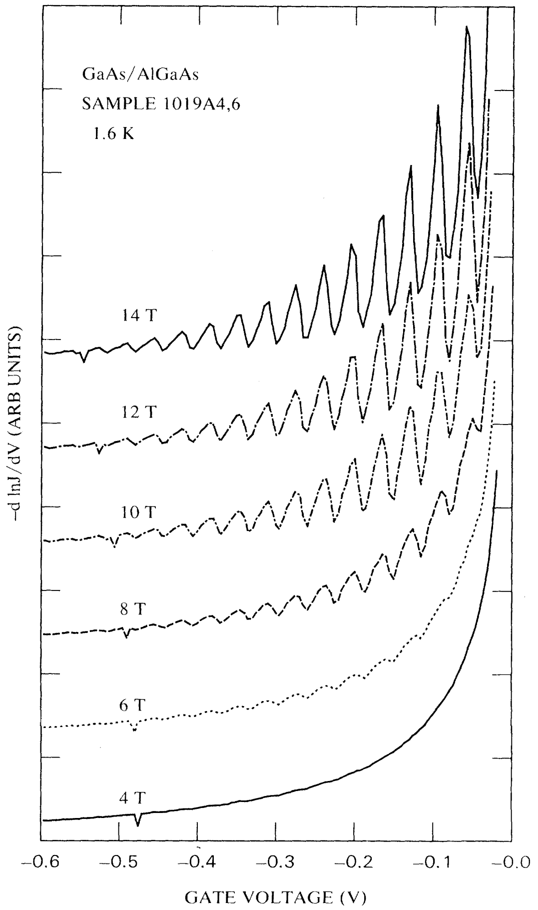


FIG. 4. Derivative of natural logarithm of current density vs V_G for different magnetic fields. The curves have been offset vertically for clarity but are all on the same scale. (The small spike between −0.48 V at 4 T and −0.54 V at 14 T is an artifact due to a measurement error of the ammeter.)

Current-voltage characteristics for reverse bias and small positive bias are shown in Fig. 3 for different magnetic fields. Current density decreases with increasing field for both polarities. At high fields, structure appears for $V_G < 0$ V; its nature is shown in Fig. 4 in which the negative voltage derivative of the natural logarithm of current is plotted as a function of V_G for 4 T $< B <$ 14 T. The periodicity is apparent. The magnitude of the oscillations is barely detectable at 4 T and increases as B increases. However, the voltage spacing, 0.036 V, and the phase of the oscillations are independent of magnetic field. Sixteen periods can be distinguished in the curves at 10 to 14 T, and almost as many at 6 and 8 T. Periodic structure in capacitance and ac conductance at 100 kHz is also seen in the same voltage range.

We propose that the structure in I-V curves arises because of creation of LO phonons by electrons accelerated by the field in insulating GaAs. The LO phonon energy from optical measurements on GaAs is 36.6 meV.[10] The role of the magnetic field is to neutralize positive donors in n^--GaAs by magnetic freezeout, thus eliminating electron scattering by positively charged donors, the major scattering mechanism that determines the electron distribution and mobility in the n^--GaAs at low temperatures. This is consistent with the threshold, ~ 4 T, for appearance of oscillations.

The situation is indicated schematically in Fig. 1(b). In high magnetic field, donors are neutralized by electrons in cyclotron orbits whose radius is comparable to the Bohr radius of the hydrogenic atom formed by donors and electrons. The Fermi level is below the edge of the available density of states in the conduction band; its position is determined by the initial donor concentration, by magnetic field, and by temperature. Electrons tunneling from n^+-GaAs are injected into insulating n^--GaAs at zero energy. As the gate voltage becomes more negative, nearly the whole potential drop is across the n^--GaAs; only a few millivolts are dropped across the $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ tunnel barrier to maintain current continuity. Since electron scattering by donors is suppressed by magnetic freezeout, electrons are accelerated ballistically. When they reach an energy of ~ 36 meV, an LO phonon is emitted and the electron is scattered back to the conduction-band edge. The process of ballistic acceleration and phonon emission is then repeated until the electron reaches the n^+-GaAs region of the substrate. It is remarkable that so many oscillation periods are seen, and that phonon emission processes are coherent over the area of the sample. The mechanism proposed is similar to that suggested by Kulik and Shekhter for the observation of electron-phonon interactions in point-contact spectroscopy of semiconductors.[11] Multiple-phonon effects have been observed in photoconductivity of InSb,[12] but we believe this is the first report of sequential single-phonon emission observed in electron transport. The observed 36-mV periodicity and its independence of magnetic field strongly suggest a ballistic-electron–optical-phonon relaxation mechanism. Furthermore, modeling of C-V data indicates that the effect is in the n^--GaAs substrate, the tunnel emitter merely supplying the electrons. We do not understand the detailed mechanism leading to the oscillations in current, since a rigorous limitation of the current by the tunnel injector would not permit its variation by these processes in the n^--GaAs.

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