UCRL-92936
PREPRINT

ONE DIMENSIONAL POLARON EFFECTS AND CURRENT
INHOMOGENEITIES IN SEQUENTIAL PHONON EMISSION

E. S. Hellman and J. S. Harris
Stanford Electronics Laboratory
Stanford, CA 94305

C. Hanna
Physics Department, Stanford University,
Stanford, CA 94305

R. B. Laughlin
Lawrence Livermore National Laboratory
University of California
Livermore, CA 94550

This paper was prepared for submittal to the
International Conference on Hot Electrons
Innsbruck, Austria
July 8-12, 1985

July 1985

Lawrence
Livermore
National
Laboratory

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

ONE DIMENSIONAL POLARON EFFECTS AND CURRENT INHOMOGENEITIES IN SEQUENTIAL PHONON EMISSION

E. S. HELLMAN⁺⁺ and J. S. HARRIS⁺, Stanford Electronics Laboratory; C. HAMMA⁺, Physics Department, Stanford University, Stanford, CA 94305 USA; R. B. LAUGHLIN⁺, University of California, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94550 USA

We have constructed a physical model to explain the tunneling current oscillations reported by Hickmott et. al. [Phys. Rev. Lett. 52, 2033] for GaAs/AlGaAs heterostructures in high magnetic fields. We propose that the periodic structure observed is due to space charge which builds up in the undepleted layer when electrons enter it with energy just below the phonon emission threshold. Such electrons interact with the lattice to form polarons whose energy is pinned to the phonon energy, and thus have a very small group velocity. The polaron effect is strongly enhanced by the confinement of the electrons by the strong magnetic field. We infer from the current-voltage data that most of the tunneling current flows through a small area of the sample. The combined model gives reasonable quantitative agreement with experiment.

I. INTRODUCTION

Hickmott et. al. recently reported periodic structure in the tunneling current of GaAs-Al_xGa_{1-x}As heterojunctions which they identified with sequential longitudinal-optical phonon emission.¹ Sequential phonon emission was previously observed in point-contact junctions by Cavenett et. al.² and in recent experiments on In-InGaAs junctions by Lu et. al.³ The heterojunction experiment differs from these in that it happens only when a strong magnetic field (>4T) is applied and occurs in the controlled environment of a sample grown by molecular beam epitaxy. This experiment has attracted attention⁴ because it is difficult to understand the mechanism by which sequential phonon emission affects the tunneling current. Electrons are believed to tunnel through the 200Å barrier and accelerate ballistically through a one micron lightly doped region. Each time an accelerated electron's kinetic energy reaches the longitudinal-optical phonon energy of 0.036 eV, the electron is thought to emit a phonon and stop. The difficulty with this picture is

that the phonon emissions occur after the electrons have tunneled. To understand this experiment, we must explain how the phonon emission communicates with the tunnel barrier. Two possibilities immediately present themselves:

- 1) The emission of phonons quantum-mechanically reflects the electrons back through the barrier.
- 2) Electrons stopped by phonon emission produce a space charge which modulates the electric field at the tunnel barrier.

The first possibility may be ruled out in this experiment because the barrier transmittance is too low. Using a tunnel barrier height of $\Delta=0.4\text{eV}$ and defining $\hbar^2 q^2/2m^*=\Delta$, this gives a barrier transmittance of $|T|^2=\exp(-2Qd)=10^{-16}$, where $d=200\text{\AA}$ is the barrier thickness. This leaves the space charge effect as the prime candidate. On the other hand, an elementary estimate of the magnitude size of the space charge shows that it would be 10^6 times too small to explain the data. In this paper we point out that there is evidence in the data that the space charge

*Supported by JSEP under contract No. DAAG-84-K-0047. ++Supported by NSF Graduate Fellowship. +Supported by NSF-MRL Program through the Center for Materials Research at Stanford University. This work was performed in part under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48.

FIGURE 1

Energy diagram of the heterojunction device at an applied voltage V . Most of the voltage drop is across the depletion layer w , with the remainder V_b falling across the barrier.

mechanism is in quantitative agreement with the existing experimental data. We argue that the current is very inhomogeneous, and that the space charge effect is further enhanced by a reduction in the electron velocity by formation of polarons in large magnetic fields.⁵

II. MAGNETIC FREEZE-OUT

Hickmott et. al. reported the observation of magnetic freeze-out of the lightly doped region of the device and invoked it to help explain the role of the magnetic field in producing phonon oscillations of the current. We believe that freeze-out does not occur on the time scale of the tunneling experiment, and thus that it does not facilitate the observation of sequential phonon emission.

In the experiment, electrons tunnel from a metallic n^+ region of Si-doped GaAs through a 200Å barrier of $Al_xGa_{1-x}As$ into a one micron lightly doped region of GaAs which is contacted by another n^+ layer from the back. The doping density N_D in the lightly doped region is approximately $10^{15}cm^{-3}$.

In the absence of a magnetic field, the lightly doped region depletes classically. This is illustrated by the band diagram in Fig. 1. In classical depletion, donors are

totally ionized and swept away by any electric field present. The voltage drop occurs across a totally ionized layer of width W next to the barrier, while the remaining volume is free of electric fields and remains neutral. The depletion width W adjusts itself to make the total potential drop equal to the applied voltage. The electric field E at the tunnel barrier is then

$$E = qN_D W / \epsilon = (2qN_D V / \epsilon)^{1/2} \quad (1)$$

which leads to a differential capacitance C of

$$C = A(\epsilon q N_D / 2V)^{1/2} \quad (2)$$

where $A = 4 \times 10^{-4}cm^2$ is the sample area and $\epsilon = 13\epsilon_0$. Depletion causes the electric field at the tunnel barrier to be larger than it would be in the absence of depletion, with a specific functional form for the enhancement of the electric field given by equation 1. The zero magnetic field capacitance data of Hickmott et. al. are well fit by this classical depletion model, using $N_D = 1.1 \times 10^{15}cm^{-3}$.

As the magnetic field increases, the enhancement of the capacitance due to depletion diminishes until, in the high-field limit, it becomes constant at the value

$$C = \epsilon A / L = 4.7pF \quad (3)$$

here $L = 1\mu m$ is the thickness of the lightly doped region. This is exactly the behavior one would expect if donors were not ionizing. We believe that the capacitance behavior measured by Hickmott et. al. is not freeze out of the donors. At intermediate field strengths, where the depletion behavior is less clear-cut, we find that the capacitance data is fit well by an expression of the form

$$C = \epsilon A / (D+W) \quad (4)$$

where D is a length that grows continuously from zero to one micron as the magnetic field increases. This is not the behavior one would expect from freeze-out, but rather that

expected if the capacitance measurement is done faster than the donors can ionize. However, the strongest evidence against freeze-out is the incompatibility of the capacitance and tunnelling measurements. If we assume that the sample at 14T is frozen out and thus that the electric field at the tunnel barrier is proportional to the applied voltage V , then $E_{14T} = V_{14T}/L$. The measured tunnel current $I_{14T}(\text{experiment})(V)$ is then a readout of the barrier conductance which one may use with the known depletion physics to predict the tunnel current at 0T:

$$I_{0T}(\text{theory}) = I_{14T}(\text{experiment})[2(V_1/V)^{1/2}] \quad (5)$$

where $V_1 = qN_D L^2 / 2\epsilon = 0.75V$ is the voltage at which the lightly doped region is entirely depleted. This expression overestimates the 0T current by about an order of magnitude. Thus, either the sample is not frozen out or the tunnel conductance is strongly magnetic field dependent.

III. ANALYSIS OF TUNNELING CURRENT

The current through a tunnel barrier of the type occurring in Hickmott's experiment is expected to be proportional to the square of the field at the barrier. The best evidence that this is the case in the experiment is that the current-voltage curves at different magnetic field can be mapped onto one another by the transformation:

$$I \rightarrow (1/2 - \beta)^2 \quad (6)$$

as shown in Fig. 2. The physical content of this transformation is that the magnetic field lowers the potential drop across the barrier by a constant proportional to β . We find $\beta = H^2$.

Classical depletion, as exhibited by the zero magnetic field capacitance data of Hickmott et. al., predicts $E = V_G^{1/2}$. Given that $I \propto E^2$, we would expect the current to be

FIGURE 2

(a) Current versus voltage as a function of magnetic field from Hickmott's data. The current decreases with increasing field strength. (b) Mapping of the current-voltage curves of Fig. 6a onto a single curve via the transformation $I \rightarrow (1/2 - \beta)^2$.

directly proportional to V . As seen in Fig. 2, this is not the case. The actual current is quadratic in V for $V < 0.4V$, so that $E_D = V$. However, the 0T capacitance data indicates $E_D = V^{1/2}$. At low voltages the local electric field producing the current is smaller than the average electric field measured by the capacitance. This presents the difficulty that the electric field producing the tunneling is weaker than the average electric field. The only way this is possible is if the point of tunneling has a higher than average conduc-

FIGURE 3
"Window" model of inhomogeneous tunneling. Electrons tunnel through a high conductance region of the barrier and neutralize a cylinder of radius R .

FIGURE 4
Current at OT as calculated from the "window" model, shown by "X"s, with the measured OT curve in solid. The agreement is good for a circular window of radius 0.75μ .

tance. The electric field might then be lower there because current pouring through the "window" neutralized donors and prevents depletion from occurring. To illustrate this behavior, let us consider a model in which electrons tunnel only through a single small circular region of radius R where the tunnel barrier is thinner than average, as illustrated in Fig. 3. We assume that impurity atoms in the cylindrical path of the tunnelling

electrons are neutralized. For a depletion layer of size w , the electric field in the center of the cylinder at the tunnel barrier will be

$$E = \frac{V_R}{R} [(V/V_R + 1)^{1/2} - 1] \quad (7)$$

where

$$V_R = qN_D R^2 / 2\epsilon \quad (8)$$

describes the voltage at which the I-V curve goes from quadratic to linear, and is a direct measure of the hole size R . Since $I = E^2$,

$$I = I_0 [(1 + V/V_R)^{1/2} - 1]^2 \quad (9)$$

Using a hole radius of 0.75μ , we obtain the close fit to the data, shown in Fig. 4. This model must not be taken too literally, but it does demonstrate how inhomogeneous tunnelling helps us to make sense of the experimental data.

Note that a hole size of $1\mu^2$ increases the charge density of the tunnelling electrons by a factor of more than 10^4 , compared to the case of uniform tunnelling. This dramatically increases the space charge effects of tunnelling electrons stopped by phonon emission.

IV. PERIODIC STRUCTURE IN CURRENT

To understand why oscillations in the current occur only when a magnetic field is applied, we begin by considering the motion of an electron through a polar lattice in the presence of a strong magnetic field. In the absence of electron-phonon coupling, we can distinguish two types of states in the semiconductor. For kinetic energies below the phonon energy, the state of the system is that of a free electron with no phonons. When the kinetic energy reaches the phonon energy, the zero-phonon, one-electron state is degenerate with states consisting of one phonon and a zero energy electron. These two types of

states are represented by the solid lines of Fig. 4. The electron-phonon interaction in a polar semiconductor such as GaAs mixes these two types of states to produce a new state with a lower energy. The dashed lines of Fig. 4 show the new states with energies pinned below the phonon energy, as a function of magnetic field.

For GaAs, the energy splitting induced by the electron-phonon interaction in the absence of a magnetic field is miniscule. When the free electrons are confined to one dimension by a magnetic field, the energy lowering is strongly enhanced because of the large (in fact divergent) density of states at zero energy. The curves of Fig. 4 are the result of a variational calculation⁵ of the dispersion relation for the single electron-phonon system in the large magnetic field case, corresponding to the experimental conditions. An important consequence of this dispersion relation is that the region just below the phonon energy has a negative effective mass. This means that a small electric field parallel to the magnetic field can have the paradoxical effect of slowing the polaron under conditions that would accelerate a free electron. The group velocity is given by the slope of the dispersion curves of Fig. 5. The velocity peaks near $k=k_{LO}$, where $\hbar^2 k_{LO}^2 / 2m^* = 0.036\text{eV}$, and then quickly falls asymptotically to zero.

In the presence of strong electric fields or phonon decay mechanisms, the polaron can break up into a free electron plus a real phonon. In regions with large electric fields, the polaron can gain enough energy from the electric field to make the transition to the free electron state. In the absence of electric fields, we expect that the emission of a real phonon occurs when the energy uncertainty for phonon decay equals the energy gap between

FIGURE 5
Energy-momentum dispersion relation for polaron as a function of magnetic field. The solid lines represent unperturbed zero and one phonon state. The electron-phonon interaction mixes these states to produce a new state with a lower energy, shown by the dashed lines.

the polaron and free electron states. Since the rate for an LO phonon in GaAs to decay into acoustic phonons is about 7ps^{-1} , the energy uncertainty is roughly 0.1 meV . This is small enough so that at the magnetic field strengths used in this experiment, the velocity of the polarons can be decreased by a factor of more than 100 compared to the peak velocity. Since the tunneling current is continuous, this implies that a large charge density must accumulate in the field-free region. The resultant space charge can then feed back to the tunnel barrier and modulate the current. This occurs when polarons are injected into the undepleted region with an energy just below the phonon energy so that they drift with very small group velocities. This produces a charge density $\delta\rho$ of tunneling electrons:

$$\delta\rho = J/v_D \quad (10)$$

where J is the current density and v_D is the

FIGURE 6

(a) Current differences measured by Hickmott as a function of magnetic field. We have plotted $J(H) - J(4T)$ in order to make the phonon oscillations easily visible. (b) Current differences, $J(H) - J(4T)$, as calculated from theory. Dip depth and width have been scaled to fit experiment.

drift velocity of the polarons. We estimate the strength of the space charge electric field to be

$$\delta E = (L-w)^2 \epsilon_p / 2\epsilon L \quad (12)$$

remembering that the voltage drop across the device is fixed at a given value V . Since $J \sim E^2$, this produces a drop in the current of magnitude

$$\delta J = 2J\delta E/E \sim 1v_p \quad (13)$$

The size of the current dip depends on the magnetic field through the drift velocity v_p which, in turn, can be read off the dispersion curve. When V approaches a multiple of the phonon energy, the polarons injected into the undepleted region are at the energy such that their velocities begin to approach zero. The minimum drift velocity, and thus the maximum current dip, can be determined by using

the phonon decay time as a cutoff for the dispersion curve. For 14T, we find this velocity to be 4.32×10^4 cm/s, using a 7 ps decay time. This works out to a $\delta E/E$ of about .005, compared to an experimental value of about .02, using the hole size parameters given above to estimate the current density at 0.3V. The discrepancy is not large considering the crudity of the model. Figure 6 shows the agreement with experiment attainable by the theory. The dips have been scaled up to match experiment by using a phonon lifetime of 25 ps. 10mV of broadening have also been put in. The dependence of the dip depth on magnetic field and voltage are modelled very well.

ACKNOWLEDGEMENT

We wish to thank T. W. Hickmott for making his experimental data available to us.

REFERENCES

1. T. W. Hickmott, F. M. Solomon, F. F. Fang, F. Stern, R. Fischer, and H. Morkoç, *Phys. Rev. Lett.* **52**, 2953 (1984).
2. B. C. Cavenett, *Phys. Rev. B* **5**, 3049 (1972).
3. P.-F. Lu, D. C. Tsui and H. M. Cox, *Phys. Rev. Lett.*, **52**, 1563 (1985).
4. J. P. Leburton, *Phys. Rev. B* **31**, 4080 (1985).
5. E. S. Hellman and J. S. Harris, to be published.
6. D. von der Linde, J. Kuhl and H. Klingenberg, *Phys. Rev. Lett.* **44**, 1505 (1980).