RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 31, NUMBER 6 15 MARCH 1985

Origin of the current oscillations in GaAs-AlGaAs tunnel junctions

J. P. Leburton
Coordinated Science Laboratory and Electrical Engineering Department,
University of Illinois at Urbana-Champaign, Urbana, Illinois 61801
(Received 27 December 1984)

This Rapid Communication reviews different interpretations provided to understand the current oscillations observed in reverse-bias GaAs-AlGaAs tunnel junctions. It is seen that the ballistic picture is contradicted by the experimental conditions. Another interpretation based on phonon-assisted tunneling appears unsatisfactory with regard to several experimental observations. An explanation based on a space-charge effect induced by phonon generation is proposed. This theoretical interpretation is in good agreement with the experiment and provides a general basis for the understanding of similar effects encountered previously in analog structures.

Recently, Hickmott *et al.*[1] observed a periodic structure in the I-V characteristics of reverse-bias n^--GaAs–undoped-AlGaAs–n^+-GaAs tunnel junctions in the presence of high-longitudinal magnetic fields at low temperature. Because the voltage periodicity corresponds to the LO phonon energy $\hbar\omega_{\mathrm{LO}}$ in GaAs, the effect was attributed to a ballistic motion of carriers successively and coherently scattered by LO phonons at carrier energy qV equal to a multiple of $\hbar\omega_{\mathrm{LO}}$. Although the period is independent of the magnitude of the magnetic field, the latter is essential for the occurrence of the oscillations since they arise at the onset of the magnetic freezout. This effect suppresses the impurity scattering and was interpreted as a condition for the ballistic transport. However, as pointed out by Hickmott, the velocity oscillations occurring in the insulating GaAs substrate cannot explain the current structures since the AlGaAs tunnel barrier rigorously controls the carrier injection in the substrate.

The purpose of this Rapid Communication is to briefly discuss the possible interpretations of this phenomenon and to propose an explanation based on a space-charge effect.

The ballistic interpretation is hardly acceptable for two important reasons. The first one was already mentioned above and deals with the current conservation in the tunnel junction. The second one is related to the occurrence of the ballistic effect. Experimental data and calculations of C-V characteristics in semiconductor-insulator-semiconductor (SIS) structures agree that most of the voltage drop is across the insulating n^--GaAs substrate, with only a slight bias at the tunnel junction.[2] Therefore, the electric field E sustained in the substrate is relatively large and varies from several hundreds to several thousand V/cm, according to the external bias. However, even at low temperature and with no impurity scattering, an oscillatory motion is only possible for $E \leq 100$ V/cm, as shown by Matulionis, Pozela, and Reklaitis[3] and Leburton and Evrard.[4] The reason is that for large fields the LO phonon scattering is unable to maintain the same phase between all the carriers, and the coherence in the velocity is lost after a few oscillations. Therefore, the analogy between this effect and the electron-phonon interaction in point contact spectroscopy,[5] as proposed in the experiment, seems invalid.

According to the commensuration between voltage and LO phonon energy, it is admitted that the current oscillations have their origin in the substrate rather than in the tunnel barrier.[1] The same conclusion was already reached by Cavenett[6] in investigating similar effects in metal-insulator-semiconductor (MIS) tunnel structures made with InSb. As the tunnel injection controls the magnitude of the current, phonon-assisted tunneling induced by hot carrier phonon generation as suggested by Katayama and Komatsubara[7] could be a possible mechanism for the oscillations. The process can be described as follows: Phonons generated by hot carriers in the semiconductor substrate cross the tunnel barrier and scatter the electrons at the gate side, increasing the tunnel probability and enhancing the current. However, the LO phonon penetration length in AlGaAs is very short,[8,9] and it is hardly possible for these phonons to interact with the electrons on the gate side. Because of the short lifetime of LO phonons, the most probable scenario is a decay of these modes into two or more acoustical (A) phonons of opposite momenta,[10] $q = \omega_{\mathrm{LO}}/nc_s$, where c_s is the sound velocity and n a small even integer. Only half of these phonons reach the gate and scatter the carriers, providing a large momentum with the wrong direction for tunneling. Therefore, an additional mechanism ($\bar{e}$-$\bar{e}$ or impurity collisions) is required in order to reverse the carrier momentum. As the number of different events involved in a single phonon-assisted mechanism is appreciable, this higher-order perturbation process has a low-occurrence probability and does not seem to be likely. Furthermore, the approach is unable to explain the role played by the magnetic field at the onset of the oscillations.

Because the two previous theories—the ballistic picture and the phonon-assisted process—are unable to provide a satisfactory explanation for the experimental observations, we are led to propose an interpretation of the current oscillations which is based on a space-charge effect. The situation can be described as follows (see Fig. 1): The electrons injected from the junction emit LO phonons in the substrate. As pointed out previously, these modes decay rapidly into two or more A phonons of opposite momenta. By traveling through the substrate, the pairs of high-energy A phonons ionize the neutral donors frozen by the magnetic field and recreate a space charge that reduces the bias across the tunnel barrier. Unlike the ballistic interpretations, this picture explains the influence of the phonon emission on the tunnel current via the space charge. Moreover, it emphasizes the role of the magnetic field, which indirectly makes the ionization process possible.

The space-charge concentration is a result of a balance between the phonon-induced ionization mechanism and the

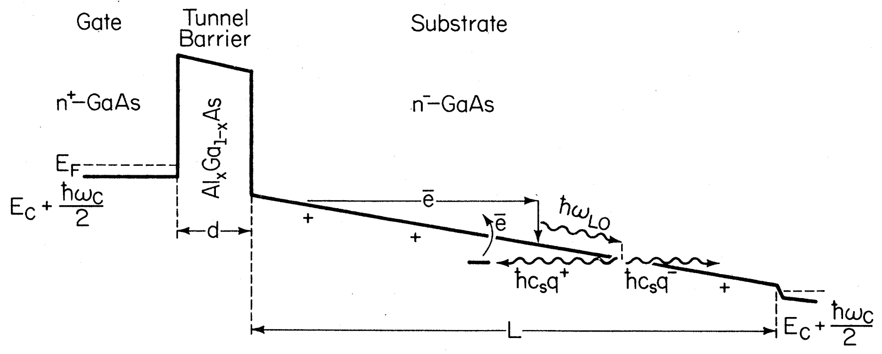

FIG. 1. Schematic energy band diagram for n^--GaAs $-Al_xGa_{1-x}As$-n^+-GaAs structure in presence of partial magnetic freezeout. The + signs in the substrate indicate the few donors ionized by the A phonons. The $q^{\pm}$ wave vectors represent the A phonons of the opposite momenta resulting from the LO phonon decay.

recombination between carriers and ionized impurities. For the former process, the flux of LO phonons created over the distance L is given by

$$\phi_{LO}=N\frac{J}{q} \; , \tag{1}$$

where J is the current density, q the electron charge, and N an integer equal to the number of LO phonons emitted by a single electron. Hence ϕ_{LO} increases by step every time the external voltage V_a satisfies the relation $qV_a=N\hbar\omega_{LO}$. The phonon decay process can be quite complicated, but for the sake of simplicity we assume that each LO phonon decays only into two A phonons with energy $E_A=\hbar\omega_{LO}/2$ and momentum $q_A=\omega_{LO}/2c_s >> q_{LO}$. If $1/\tau_g$ is the probability of ionizing a neutral donor, then the rate of electron generation is given by

$$G=2NJ/qc_s\tau_g \; . \tag{2}$$

On the other hand, the carrier recombination rate is given by

$$R=J/qv\tau_r \; , \tag{3}$$

where v is the average carrier velocity and $1/\tau_r$ is the recombination probability. The steady-state condition requires $G=R$ or

$$2N/c_s\tau_g=1/v\tau_r \tag{4}$$

independently on the current density. Because $1/\tau_r$ and $1/\tau_g$ are proportional to the ionized donor concentration N_D^+ and to the neutral donor concentration $N_D-N_D^+$, respectively, we can write

$$1/\tau_r=N_D^+P_r \; , \tag{5a}$$

$$1/\tau_g=(N_D-N_D^+)P_g \; , \tag{5b}$$

where P_r and P_g are the recombination and generation probability per center. Finally, we obtain

$$N_D^+=2N(vP_g/c_sP_r)N_D \; , \tag{6}$$

where we neglect N_D^+ compared with N_D. Nonradiative electron capture and donor ionization are very complicated processes which can be manifested in different ways.[11] We do not intend to calculate exactly the different probabilities for these two processes. We rather determine roughly the order of magnitude of the ratio P_g/P_r in order to estimate the magnitude of the space charge. If we assume that the same kind of phonons are involved in both R and G processes, the ratio is independent on the value of the coupling parameters between electrons and phonons, and we have

$$P_g \propto \sum_{i,n}\int dk|\langle k,n|e^{i\mathbf{q}\cdot\mathbf{r}}|\psi_b\rangle|^2\,\delta\left(\frac{\hbar^2k^2}{2m}+n\hbar\omega_c+E_i-\frac{\hbar\omega_{LO}}{2}\right) , \tag{7a}$$

$$P_r \propto \sum_{i}\int d^3q|\langle\psi_b|e^{-i\mathbf{q}\cdot\mathbf{r}}|k,n\rangle|^2\,\delta\left(\frac{\hbar^2k^2}{2m}+n\hbar\omega_c+E_i-\hbar c_sq\right) , \tag{7b}$$

where $|k,n\rangle$ is the wave function of the Landau levels with energy $n\hbar\omega_c+\hbar^2k^2/2m$ in the conduction band, and $|\psi_b\rangle$ is the donor wave function corresponding to the level E_i calculated from the bottom of the first Landau level. In the former expression, the integration is carried out over all possible k and n because the phonon wave vector is determined by the decay process of LO phonons. In strong magnetic fields $\hbar\omega_c\sim 20$ meV for $B=12$ T. Therefore, only the first Landau level $n=0$ contributes significantly to P; meanwhile the separation between donor levels E_i becomes important,[11] and only large $q\sim\omega_{LO}/2c_s$ values contribute significantly to the last expression. Then $k<<q$ in both cases, and the matrix elements are isotropic in a first approximation. We obtain

$$P_g \propto \sum_{i}\int dk|\langle 0|e^{i\mathbf{q}\cdot\mathbf{r}}|\psi_b\rangle|^2\delta\left(\frac{\hbar^2k^2}{2m}+E_i-\frac{\hbar\omega_{LO}}{2}\right) , \tag{8a}$$

$$P_r \propto \sum_{i}\int dq\, q^2|\langle\psi_b|e^{-i\mathbf{q}\cdot\mathbf{r}}|0\rangle|^2\delta\left(\frac{\hbar^2k^2}{2m}+E_i-\hbar c_sq\right) . \tag{8b}$$

Because the phonon wave vectors involved in the two processes are comparable, the matrix elements are roughly identical. Moreover, the transitions occur between the same set of donor states. Therefore, we can assume that the donor states can be represented by an average level $\bar{E}_i$ that for the sake of simplicity we choose identical in the R and G processes. Then we obtain

$$\frac{P_g}{P_r}=\frac{\sqrt{2}\pi(mc_s^2)^{3/2}\hbar\omega_c}{(\hbar\omega_{LO}/2-\bar{E}_i)^{1/2}(\hbar^2k^2/2m-\bar{E}_i)^2} \; . \tag{9}$$

For $\bar{E}_l = \hbar\omega_{\mathrm{LO}}/4$ from the edge of the Landau level and $v = \sqrt{2\hbar\omega_{\mathrm{LO}}/m} \sim 4.4\times 10^7$ cm/sec, the ionized donor concentration is given by

$$N_D^+ \simeq 6\times 10^{-3} N N_D \ , \tag{10}$$

which for the experimental conditions where $N_D = 1.4 \times 10^{15}/\mathrm{cm}^3$ represents a space charge of $\sim 8.4\times 10^{12} N/\mathrm{cm}^3$. This corresponds to a voltage drop in the substrate of $\Delta V_a = 7.2N$ mV or about 20% of the applied voltage. Therefore, in the conditon of magnetic freezeout, the bias across the tunnel barrier is given by $V_T = (V_a - \Delta V_a)d/L$, i.e., a few percent of the external voltage V_a with $d \sim 200$ Å and $L \sim 1$ μm. Hence the voltage across the tunnel junction undergoes discrete tiny variations each time that $qV_a = N\hbar\omega_{\mathrm{LO}}$.

In the WKB approximation, for weak bias, it can be shown that the tunnel current is given by

$$J = J_0(1 - e^{-\alpha V_T}) \ , \tag{11}$$

where J_0 and α are constant parameters characteristic of the barrier and the doping level on each side of the junction. In this derivation we have ignored the effect of the magnetic field on the tunnel process in agreement with the experimental observations. We have also assumed a large doping difference between the gate and the substrate. By taking the logarithmic derivative of J with respect to V_a, we obtain

$$\frac{1}{J}\frac{dJ}{dV_a} = \frac{\alpha}{e^{\alpha V_T} - 1}\left[\frac{d}{L} - \frac{q\Delta V_a}{N\hbar\omega_{\mathrm{LO}}}\delta\left(\frac{qV_a}{\hbar\omega_{\mathrm{LO}}} - N\right)\right] \ , \tag{12}$$

where the delta function arises from the sudden variation of the space charge. In reality, an energy distribution exists among the carriers which broadens the current variations. The important fact, however, is that peaks appear at the correct voltage value in the current derivative. Moreover, these peaks are negative, which means that the LO phonon emission induces minima in the I-V characteristic and not maxima as predicted by the phonon-assisted tunneling picture. This conclusion is in perfect agreement with previous experimental observations made by Cavenett on MIS structures.[6] Hence our approach seems applicable to this latter experiment too, and some features of charge transport in both SIS and MIS structures can be described by a similar process, i.e., a resistance enhancement caused by the disturbance of the LO phonon distribution. Therefore, the common nature of the two phenomena provides some confidence in the validity of our theory.

In summary, we have shown that the space-charge effect induced by phonon generation provides a realistic explanation of the current oscillations in the I-V characteristics of reverse bias GaAs-AlGaAs tunnel junctions. Our simplistic approach accounts for all the aspects of the experimental findings. Moreover, the model constitutes a general basis for the understanding of a broad range of oscillatory effects observed at low temperature in analog semiconductor tunnel junctions.

The author is grateful to K. Hess for his continuous encouragement and fruitful discussions and thanks Mrs. E. Kesler for her technical assistance. This project is supported by the Joint Services Electronics Program.

---

[1] T. W. Hickmott, P. M. Solomon, F. F. Fang, F. Stern, R. Fischer, and H. Morkoç, Phys. Rev. Lett. **52**, 2053 (1984).

[2] T. W. Hickmott, P. Solomon, R. Fischer, and H. Morkoç, Appl. Phys. Lett. **44** 30 (1984).

[3] A. Matulionis, J. Pozela, and A Reklaitis, Phys. Status Solidi (a) **31**, 83 (1975); **35**, 43 (1976).

[4] J. P. Leburton and R. Evrard, J. Low Temp. Phys. **32**, 323 (1978).

[5] I. O. Kulik and R. I. Shekhter, Phys. Lett. **98A**, 132 (1983).

[6] B. C. Cavenett, Phys. Rev. B **5**, 3049 (1972).

[7] Y. Katayama and K. F. Komatsubara, Phys. Rev. Lett. **19**, 1421 (1967).

[8] C. Colvard, T. A. Gant, M. V. Klein, R. Merlin, R. Fischer, H. Morkoç, and A. C. Gossard, Phys. Rev. B **31**, 2080 (1985).

[9] K. Hess and P. Vogl, Solid State Commun. **30**, 807 (1979).

[10] R. Orbach, Phys. Rev. Lett. **16**, 15 (1966).

[11] See, e.g., G. E. Stillman, C. M. Wolfe, and J. O. Dimmock, in *Semiconductors and Semimetals*, edited by R. K. Willardson and A. C. Beer (Academic, New York, 1977), Vol. 12, p. 169.