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Hot phonon-assisted electron resonant tunnelling through a donor level in a quantum well

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Abstract

We develop a theoretical model of resonant tunnelling assisted by non-equilibrium acoustic phonons through a donor state in a quantum well and compare the numerical results of the phonon-induced current with recent experiments. Qualitative agreement has been obtained, although the calculated amplitudes are 1–2 orders of magnitude smaller than the experimental values. A possible model to explain this is proposed.

Keywords: Assisted resonant tunnelling; Non-equilibrium phonons

1. Introduction

Recently, we have made the first observation of resonant tunnelling through donor levels confined in a quantum well assisted by a beam of non-equilibrium acoustic phonons [1–3]. In this work, we present a theoretical investigation of this nonlinear system by the method of non-equilibrium Green functions (NGF) [4], which consistently describes the non-equilibrium spectrum and population of the impurity levels.

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2. Experimental

The experimental system consists of a GaAs/(AlGa)As double barrier heterostructure in which the centre of the well is δ-doped with Si donors to a density $4 \times 10^9\,\mathrm{cm}^{-2}$. Non-equilibrium phonons are generated by applying electrical pulses to a constantan heater evaporated opposite the device. The resulting transient change in the tunnel current is measured as a function of applied bias across the device. We also measure the change in current when the equilibrium temperature is increased from T_{eq1} to T_{eq2} [1–3].

Fig. 1 shows the change in current ΔI for both polarities of the bias when the equilibrium temperature is increased from $T_{eq1} = 1.6\,\mathrm{K}$ to $T_{eq2} = 4.2\,\mathrm{K}$ (solid curves) and by a pulse of non-equilibrium phonons at $T_h \sim 10\,\mathrm{K}$ when the sample is at $T_{eq} = 4.2\,\mathrm{K}$ (dashed

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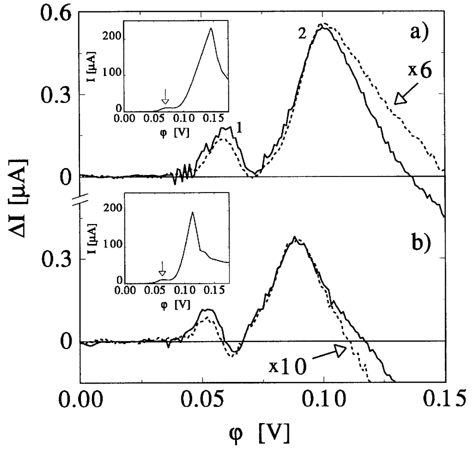

Fig. 1. Experimental results for (a) forward bias and (b) reverse bias. The solid curves show the change in tunnel current ΔI when the equilibrium temperature is increased. The dashed curves show the change produced by a pulse of non-equilibrium phonons.

curves). The insets show the corresponding I–V characteristics at $T_{\mathrm{eq}} = 4.2\,\mathrm{K}$. The main peak in I–V corresponds to resonant tunnelling through the lowest bound state in the well. The peak observed near the onset of the main resonance (indicated by the arrow) results from tunnelling through the donor ground states [5]. In this range, the ratio of the potential drop across the first barrier to the total bias is estimated to be 0.3.

The current changes ΔI show two peaks, 1 and 2, separated by a minimum whose position coincides with that of the donor peak in I–V. The amplitudes ΔI of peak 1 compared with the current I at the resonant donor peak for forward (reverse) bias are 2.7% (2.5%) and 0.44% (0.18%) for equilibrium and non-equilibrium measurements, respectively. In Refs. [1–], peak 1 (2) was attributed to phonon-assisted tunneling through the ground state of the donor as a result of phonon absorption – anti-Stokes (emission – Stokes). Theoretical calculations [8] show that both emission and absorption processes contribute here to both peaks 1 and 2. In peak 2 assisted tunneling through the bound state of the well should be also reflected, which can be clearly resolved in magnetic fields.

3. Theoretical model

We model this experimental system by a donor level confined in the well coupled via the tunnelling barriers to the emitter and collector reservoirs, which for simplicity we assume to be both 2D electron gases. We also assume the donor level is coupled to bulk LA phonons via the deformation potential [6]. This model system is described by the Hamiltonian

$$\begin{aligned} H = & \sum_{k;\,\alpha=\mathrm{L,R}} E_{k,\alpha} c^{+}_{k,\alpha} c_{k,\alpha} + E_0 d^{+} d \\ & + \sum_{k;\,\alpha=\mathrm{L,R}} \gamma_{k;\alpha}(c^{+}_{k,\alpha} d + d^{+} c_{k,\alpha}) + \sum_q \hbar\omega_q b^{+}_q b_q \\ & + \sum_q F(q) M(q) d^{+} d (b_q + b^{+}_{-q}), \end{aligned} \tag{1}$$

where $c^{+}_{k,\alpha=\mathrm{L,R}}$ ($c_{k,\alpha=\mathrm{L,R}}$) and $E_{k,\alpha=\mathrm{L,R}}$ are the creation (annihilation) operators and energies for conduction electrons in the left (L) and right (R) reservoirs. d^{+} (d) and E_0 are, respectively, the creation (annihilation) operators and energy for the donor level, $\gamma_{k,\alpha=\mathrm{L,R}}$ are the coupling parameters between the level and the reservoirs, b^{+}_q (b_q) are the phonon creation (annihilation) operators for momentum $q, \hbar\omega_q$ is the phonon energy and $M(q)$ is the matrix element for electron interaction with LA phonons. We take the deformation potential constant $D = 11\,\mathrm{eV}$ [6]. $F(q)$ is the square of the donor wave function in momentum representation. In real space this is taken to be a Gaussian function of half-width $\sigma = 10\,\mathrm{nm}$, multiplied by the wave function for the lowest subband of a quantum well of width $w = 5\,\mathrm{nm}$ [7]. The reservoirs are assumed to have constant densities of states (2D) and the Fermi energy in the emitter reservoir is taken to be 1 meV. The DC bias is approximated by taking different chemical potentials in the reservoirs $\mu_{\mathrm{L,R}}$, assuming these shift under bias by the same amount but in opposite directions with respect to the equilibrium chemical potential μ_0 and the fixed position of the donor level E_0. We neglect electrostatic effects associated with charge build-up in the well. For the equilibrium case we use a Bose–Einstein distribution $n_{\mathrm{BE}}(\hbar\omega, T_{\mathrm{eq}})$ and for the non-equilibrium case, the distribution is described by combining Bose–Einstein functions for cold and hot phonons: $f_{\mathrm{P}}(\omega) = (1 - c_{\mathrm{p}}) n_{\mathrm{BE}}(\hbar\omega, T_{\mathrm{eq}}) + c_{\mathrm{p}} n_{\mathrm{BE}}(\hbar\omega, T_{\mathrm{h}})$. We take $c_{\mathrm{p}} = 0.015$ to obtain the ratio between the equilibrium and non-equilibrium signals observed in the experiments.

The system is described by non-equilibrium correlation functions, which fulfil a set of integral Kadanoff–

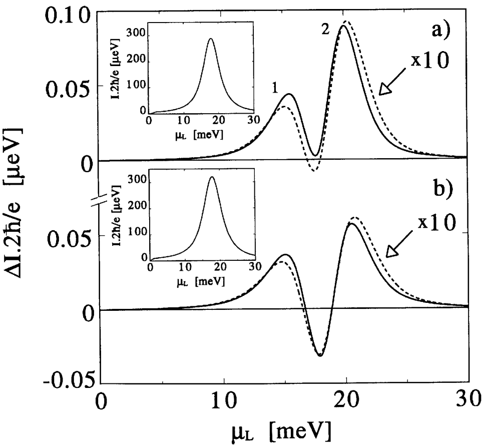

Fig. 2. Calculated phonon-assisted current for two sets of coupling parameters. The solid curves show the change in tunnel current when the equilibrium phonon temperature is increased. The dashed curves represent the change produced by a pulse of non-equilibrium phonons. In both cases the electron temperature is held constant.

Baym equations in a frequency representation [8]. We solve these equations in the presence of tunnelling and including electron–phonon interaction, described by the Migdal approximation for the self-energy [6]. From the resulting correlation functions we calculate the total resonant tunnelling current [9].

In Fig. 2, we simulate the experimental results by theoretical calculations for two sets of effective coupling parameters [8] $\gamma_L = 7$ meV, $\gamma_R = 5$ meV (a) and $\gamma_L = 6$ meV, $\gamma_R = 5$ meV (b), which model the experimental widths of the resonance and the slight asymmetry of ΔI in Fig. 1 for the two polarities of the DC bias. These parameters are consistent with the larger charge build up at the main peak in I–V in case (a) compared with case (b) as is evident from the insets of Fig. 1. In principle there are two possible contributions to the signal: one from the change of phonon-assisted tunnelling and the other from an increase in electron temperature (we refer to this as the heating effect). The solid curves show the change in current when the equilibrium phonon temperature is increased from $T_{eq1} = 1.6$ K to $T_{eq2} = 4.2$ K, as in the experiment, but the electron temperature is maintained at T_{eq1} to prevent electron heating. The dashed curves show the change in current produced by the change in phonon distribution from the Bose–Einstein form $n_{BE}(\hbar\omega, T_{eq2})$ to the distribution $f_P(\omega)$ from non-equilibrium phonons at $T_h = 10$ K while keeping the electron temperature at T_{eq2}. Inhomogeneous broadening of the donor level with half-width $\sigma_i = 0.8$ meV has been included, which gives ΔI–V responses of very similar form to those observed experimentally [8]. Calculations show that both peaks 1 and 2 correspond to phonon-assisted tunnelling as a result of phonon absorption and emission. There is also a minimum at resonance in agreement with expectation, resulting from a shift in oscillator strength to the two phonon satellites. However, for the parameters used, the change in the equilibrium current at peak 1 is about 0.016% of the total current at the donor peak in I–V, which is about 200 times smaller than that observed experimentally although this discrepancy decreases to 20 at higher temperatures ($T_{eq1} = 3.9$ K, $T_{eq2} = 10$ K). The amplitudes of the signals are sensitive to the parameters used ($D, \gamma_{L,R}, \sigma_i, \ldots$), but, for reasonable choices, the values obtained always remain appreciably smaller than those observed.

We have also calculated the change in the current resulting from a heating of the electrons in the emitter. The calculations show that heating the electrons by the same amount as the phonons gives a much larger signal than only heating phonons. Our model shows that heating of electrons from $T_{eq1} = 1.6$ K to $T_{eq2} = 4.2$ K changes the current by 3.6%, which is close to the changes observed in Fig. 1. This suggests that electron heating may play an important role in the above experiments. However, heating of electrons in the 2D emitter cannot account for the observed form of the ΔI–V signal. Its effect is the redistribution of electrons near the Fermi level, which gives rise to a positive (negative) peak below (above) the level position and no change at resonance. But the observations in Fig. 1 show a minimum at resonance and two positive peaks at both its sides.

In order to get quantitative agreement between the experimentally observed and calculated signals we need therefore to consider mechanisms which increase the coupling of the electron states to phonons and at the same time reduce the electron heating effects. One mechanism may be the formation of localised states when electrons in the low density emitter become weakly bound by the ionised donors in the well. The wave function of such a localised emitter state will be strongly asymmetric, which may increase the electron–phonon coupling strength and the energy gap bewtween the localised level and continuum q in the 2D emitter (a few meV [10]) would reduce the effect of heating. On the other hand, such states in the emitter could allow more complex electron distribution in the emitter alone, where heating might play a dominant role.

4. Conclusion

In summary, we have developed a theoretical model to describe resonant tunnelling through a donor level in a quantum well assisted by non-equilibrium phonons. The numerical results are compared with recent experiments. While the model explains qualitatively the main experimental features if electron heating in the emitter is neglected, the phonon-induced signals are smaller than those observed experimentally. The absence of heating in the experiments may be explained if tunnelling is predominantly through a bound state in the emitter due to the donor in the well. This could also result in the increased electron–phonon coupling required to explain the stronger experimental response. We cannot however rule out the possibility that heating might be an important effect if more complex electron dynamics are considered in the emitter.

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