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Temperature dependence of the resonant-tunneling process in a double-barrier diode

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We use differential absorption spectroscopy to study experimentally the temperature dependence of the accumulated charge and transit time in a double-barrier resonant-tunneling diode. We find that both are approximately constant over a broad temperature range (10 K $< T <$ 300 K). We show that the electrons experience inelastic-scattering events while they cross the structure, and that they are thermalized with the lattice at that temperature range. We discuss these results in the context of present models of resonant tunneling.

The substantial improvements achieved in recent years in the growth and fabrication of high-quality resonant-tunneling double-barrier diodes (DBD) has made them a convenient tool for testing tunneling phenomena.[1] An interesting question, which has attracted much attention and is still a subject of controversy, is that of coherence in resonant tunneling. Resonant tunneling is commonly described as a coherent Fabry-Perot-like process, in which the two potential barriers play a role similar to that of the mirrors in an optical resonator.[2] It has been claimed, however, that the current-voltage (I-V) behavior of the DBD, which is characterized by negative differential resistivity, can be explained by a sequential model of tunneling from three-dimensional to two-dimensional density of states.[3,4] In this picture the tunneling process is not coherent, and scattering events occur while electrons cross the quantum well (QW).[4] Inelastic scattering is of special importance in the context of coherence in tunneling. Such processes randomize the phase of the electrons wave function and destroy its coherence. The influence of these interactions on the transport properties was studied phenomenologically by Stone and Lee[5] and by Buttiker.[4] The effect of the interaction with phonons was explicitly addressed in several recent works by Glazman and Shekhter[6] and by Wingreen, Jacobsen, and Wilkins.[7] It was shown that even though inelastic scattering by phonon destroys the coherence of the transport through the structure, they have a very little effect on the measurable transport properties of the resonant-tunneling diode. More specifically, it was predicted in these works that both the integrated transmission and the transit time through the structure should remain unchanged when resonant tunneling occurs in the presence of inelastic scattering.

In this paper we study experimentally the temperature dependence of the accumulated charge in the QW region of a DBD. We bring experimental evidences that the tunneling electrons experience inelastic-scattering events, yet the value of the peak charge density in the well remains approximately constant over a temperature range of 10–300 K. We show that the electrons which are accumulated in the well lose their kinetic energy and are thermalized with the lattice at all temperatures. We find that the transit time τ, which is deduced from the ratio between the accumulated charge density σ and the current density through the diode J, is unaffected by the large variation of the temperature. We show a good agreement of this constant transit time with the tunneling time through the exit barrier. Finally, we discuss our results in the context of present theoretical models for resonant tunneling.

Most optical measurements of charge accumulation in DBD were done using photoluminescence techniques.[8,9] The experimental technique we used in this study is differential absorption spectroscopy (DAS). This technique monitors the changes in the absorption spectrum due to the presence of carriers or fields applied to the sample. In its simplest form it is a manifestation of the Pauli exclusion principle, which inhibits transitions into states filled by electrons. This in turn causes a bleaching of the absorption at the corresponding transition energy. Hence, the DAS signal reproduces the energy distribution of the electrons. At low densities, where only the near gap states are filled, the bleaching process corresponds to saturation of the exciton transition.[10] It was shown that the saturation of the exciton transition in QW's comes primarily from the occupation of the electron states from which the exciton wave function is built.[10] Note that very low light intensities can be used such that the measurement process is essentially not invasive. Therefore one can get reliable and calibrated values for the charge density in quantum-well devices. We have demonstrated the strength of this technique by performing measurements of charge densities in a modulation doped field effect transistor[11] and recently in a resonant-tunneling diode.[12]

The sample we studied was a symmetric DBD composed of $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ with well width 45 Å and barrier width 70 Å. The zero-bias Fermi energy in the emitter and collector is $E_F^0 = 55$ meV. The detailed description of the sample structure is given in Ref. 12.

This material system is particularly suitable for this study because the $In_{0.52}Al_{0.48}As$ forms high barriers, of almost 0.5 V, which suppress residual current due to thermionic emission at high temperatures.[13] Moreover, it is grown on a wide band-gap substrate, InP, which acts as a transparent optical window for transmission measurements at the wavelengths of interest. The processed diodes showed a profound negative differential resistance, and peak to valley ratios of 30:1 and 4:1 were measured at 10 and 300 K, respectively. The switching voltage and peak current density at 10 K were 0.4 V and 65 A/cm^2, respectively. This current density is lower by a factor of 2 relative to the sample studied in Ref. 12, probably because of inhomogeneities in layer thickness and doping across the wafer.

Experiments were performed in a continuous flow variable-temperature liquid-helium cryostat. The output of a low intensity monochromator was imaged on a DBD mesa (the incident intensity was ≈ 100 $\mu W/cm^2$) and the transmitted light T was detected using a germanium p-i-n detector. The voltage on the diode was modulated between $V=0$ and the switching voltage (peak current) $V=V_{peak}$ at a low frequency (≈ 300–400 Hz), and the corresponding change in transmission ΔT was analyzed using a lock-in technique. At the spectral range around the QW absorption edge the lock-in signal is the difference in the transmission of the QW between 0 V (empty well) and V_{peak} (filled well). In the small signal regime we get that $\Delta T/T \simeq -\Delta \alpha l$, where $\Delta\alpha$ is the change in the absorption coefficient and l is the well thickness. Positive and negative $\Delta T/T$ represent a decreased and an increased absorption, respectively.

Figure 1 shows four DAS measurements taken at $T=10$, 90, 170, and 290 K. The assignment of the different spectral features was described in Ref. 12. From high to low photon energies one distinguishes two positive peaks due to the bleaching of the light-hole (lh) and the heavy-hole (hh) excitons, a positive lobe due to the accumulation layer at the emitter and a negative one due to the formation of a depletion layer at the collector. It is evident in all the DAS measurements that the QW signal is confined to a narrow spectral range at or near the excitons resonances. At low temperatures the corresponding occupied electron states are mainly the lowest k states of the well, within one exciton binding energy from the bottom of the QW conduction band. In the high-temperature spectra we can see a tail, which extends to higher energies, with width comparable to k_BT. Note that at V_{peak} the tunneling electrons enter the well with transversal kinetic energies between 0 and E_F, the quasi-Fermi-energy at the emitter, which for our sample is larger than one LO phonon energy. ($E_F > E_F^0$ due to the accumulation region at the emitter.) Without transversal energy relaxation the electron distribution in the well should have been constant from the bottom of the conduction subband up to E_F above it. The fact that we observe a signal only at the energy range, which corresponds to transitions into the bottom of the conduction subband, indicates that the electrons lost their transversal kinetic energy. This process can occur because the relatively thick and high barriers give rise to a long transit time (~ 100 ps), which is significantly longer than the typical time for emission of an LO phonon (<1 ps). At temperatures higher than ~ 70 K the mean time between collisions (absorption) of LO phonons becomes shorter than this transit time and at room temperature a collision with an LO phonon occurs every 100–200 fs.[14] Since the phase space for phonon absorption is large, this process becomes dominant at high temperatures, and the interaction of the electrons in the well with phonons is significantly enhanced. Phonon emission and absorption processes are therefore very likely, and the electrons are able to thermalize with the lattice. Thus, the observed electron energy distribution reflects the occurrence of this relaxation and thermalization process.

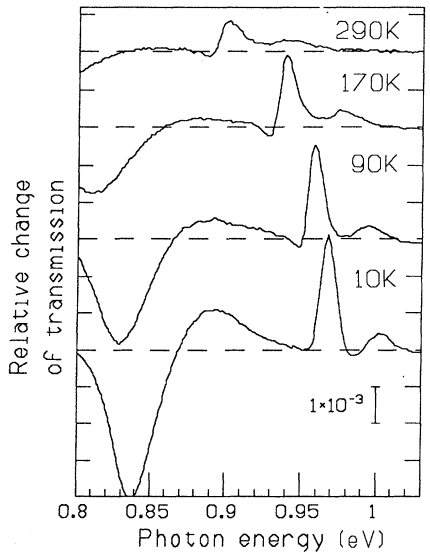

FIG. 1. Differential absorption spectra at four different temperatures measured at the peak current point.

To analyze the temperature dependence of the accumulated charge in the QW we have to examine the temperature dependence of the DAS. We recall that the absorption spectrum of the QW can be expressed as

$$\alpha^{(0)}(\hbar\omega)=\sum_n \alpha_{X,n}^{(0)}(\hbar\omega)+\alpha_{C,n}^{(0)}(\hbar\omega)$$

where the sum runs over the QW hh and lh transitions, and X and C denote the excitonic and the continuum contributions, respectively. As N electrons per unit area are introduced into the well, the excitonic contribution to $\alpha(\hbar\omega)$ is reduced by $\Delta\alpha_X(\hbar\omega,N)$, and the continuum contribution is reduced by $\Delta\alpha_C(\hbar\omega,N)$. It is well known that $\Delta\alpha_X$ is related to the bottom-band occupation and hence decreases as temperature is increased.[10] On the other hand, $\Delta\alpha_C$ is related to the occupation of higher k states and therefore increases with temperature. The integrated area under the DAS is proportional to $\int(\Delta\alpha_X+\Delta\alpha_C)d(\hbar\omega)$ and, therefore, should not have a strong dependence on temperature if N is constant. Figure 2(a) shows the integrated area under the measured DAS as a function of temperature. Integration is performed over the energy range of the QW transitions. As can be seen there is only a slight monotonic decrease of

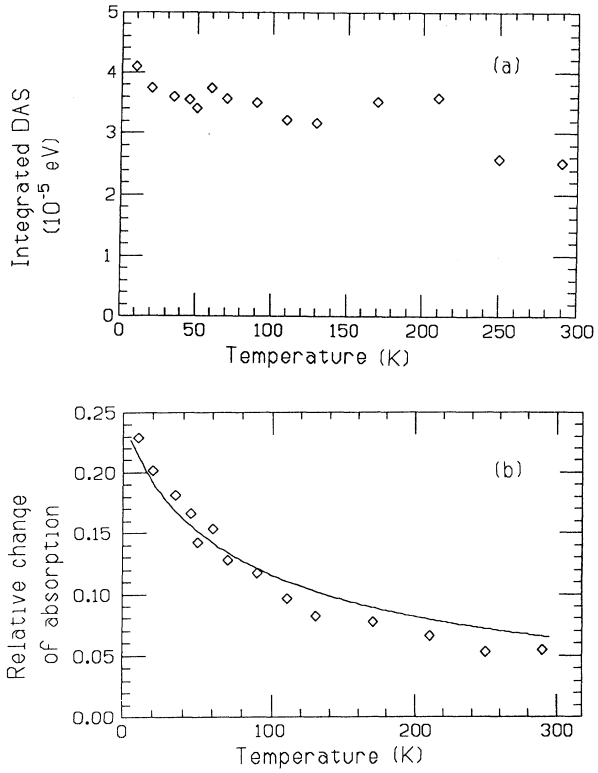

FIG. 2. (a) The integrated area under the measured DAS curves as a function of temperature. (b) The relative change of the heavy-hole exciton area as a function of temperature. The solid line is the calculated $N/N_s^e(T)$ for $N=2.5\times10^{10}$ cm^{-2}.

about 30% as the temperature is increased from 10 to 300 K. This is qualitative evidence for conservation of total charge density.

To substantiate this finding let us focus on the temperature dependence of the *excitonic* contribution to the DAS. We perform a careful fit of the DAS at each temperature to a curve which is a sum of differential signals from the hh and lh excitons and the continuum. The excitons are assumed to have Gaussian line shape and the continuum is described by a step function multiplied by the Sommerfeld enhancement. The exciton binding energy is taken as 9 meV.[15] We include both the bleaching due to phase-space filling and the small contribution due to a Stark shift of the QW energy level. Figure 2(b) shows the relative integrated *change* of the area under the hh exciton, Δ_{hh}/A_{hh}, as a function of temperature, where $\Delta_{hh}=\int\Delta\alpha_{hh}(\hbar\omega)\times d(\hbar\omega)$ and $A_{hh}=\int\alpha_{hh}(\hbar\omega)d(\hbar\omega)$. $A_{hh}(T)$ is obtained by measuring the absorption spectra at various temperatures of a 50 QW calibration sample with identical well and barrier width, which was grown under the same conditions as the DBD, and is found to have only very little dependence on temperature. The saturation of the excitonic absorption was studied in Ref. 10. It was shown there that in the limit of low carrier density in the well the relative change of the exciton absorption is proportional to N/N_s, where N_s is a characteristic saturation density. It was also shown there that N_s increases with temperature due to the thermalization process of the electrons. At high temperatures a large fraction of them are at high k states, hence reducing the exciton bleaching. It is expected, therefore, that the relative change of the exciton absorption would decrease with temperature. To analyze this decrease quantitatively we rederive the exciton saturation formulas for the case of electrons only.[10,16] We calculate the explicit temperature dependence of $N_s^e(T)$, the exciton saturation density in the presence of electrons, and its relation to $N_s^{e-h}(T)$, the exciton saturation density due to electron-hole pairs. This relation is used to determine N_s^e from optical measurements of N_s^{e-h} at 10 K. The solid line in Fig. 2(b) shows N/N_s^e as a function of temperature for the calculated $N_s^e(T)$ and for a constant N. It can be seen that the decrease in Δ_{hh} is consistent with the expected increase of the saturation density N_s^e over that temperature range. We can thus conclude that the temperature dependence of Δ_{hh} is due to that of N_s^e and that the electron density in the QW is essentially independent of the temperature.

The absolute value for N can be estimated in two ways.[17] The first is a best fit to the curve of Fig. 2(b), which gives $N\sim2.5\times10^{10}$ cm^{-2}. Alternatively, we can apply the method used in Ref. 12, which is based on the peak values for $\Delta\alpha_{hh}$ and α_{hh} at 10 K, and get $N\sim3.8\times10^{10}$ cm^{-2}.

Figure 3 shows the dependence of the current density J on temperature. As can be seen clearly, the peak current density, $J_{peak}\approx60$ A/cm^{-2}, remains almost constant over the entire temperature range, and has a little monotonic dependence on temperature. Dividing the accumulated charge density σ by the current density J we can get the transit time through the structure $\tau=\sigma/J\approx65$ ps. Since both σ and J are approximately constant over that temperature range, it follows that τ is also unaffected by the temperature change.

The observation of the temperature independence of the accumulated charge density, current density, and transit time can be explained in terms of existing models of tunneling. The coupling of the resonant state to the phonon bath modifies its width due to phonon-assisted tunneling and scattering processes, and thereby changes the transmission curve. Estimates of this width at room temperature are of the order of a few meV.[1] Nevertheless, since the Fermi energy at the emitter is much larger than both

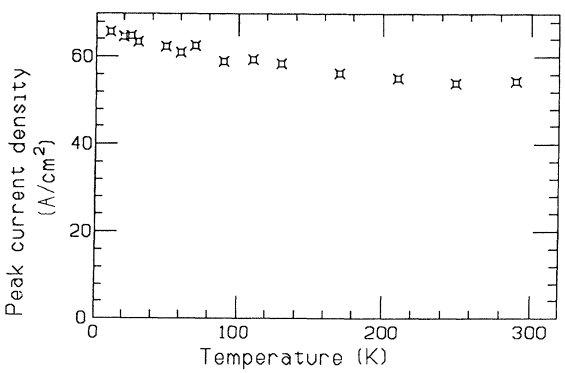

FIG. 3. The peak current density as a function of temperature.

the elastic and the inelastic widths, the transport properties are related to the *integrated* transmission probability. The constant charge and current densities show that this integrated probability is insensitive to inelastic scattering by phonons, in agreement with both phenomenological[5] and explicit[6,7] models of resonant tunneling. The electron transmission probability curve, therefore, broadens with temperature, and the peak decreases between 10 and 300 K. The transit time, which is sometimes termed the tunneling time, can be related in the coherent tunneling limit to the decay rate through the right (exit) barrier,[18] Γ_R, by $\tau = \hbar/\Gamma_R$. It was shown by Wingreen, Jacobsen, and Wilkins[7] that this transit time is unaffected by inelastic-scattering processes and remains the inverse of the elastic width. A transfer-matrix calculation of Γ_R yields $50 < \tau < 140$ ps, depending on the band discontinuity which is assumed, in a reasonable agreement with the experimental value for $\sigma/J \approx 65$ ps. Bearing in mind that at room temperature an electron experiences a few hundred collisions with LO phonons during the tunneling process, this insensitivity is a remarkable result. It should be noted that other scattering mechanisms, like elastic scattering by interface roughness, also contribute to the resonant width,[13] but they do not have a measurable effect on the transit time. Finally, we would like to point out that there could be double-barrier structures for which this sum rule of the integrated transmission does not hold.[19] In such cases we expect inelastic scattering to have a profound effect on the transport properties.

To summarize, inelastic-scattering processes involving the tunneling electrons were shown to occur in the well, such that the electrons distribution is thermalized with the lattice at all temperatures. Nevertheless, the three major physical quantities that characterize the tunneling process in DBD, the current density, the stored charge, and the transit time, are insensitive to a large temperature change. We have shown that this insensitivity to inelastic scattering by phonons is consistent with a coherent quantum-mechanical description of tunneling.

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