Direct determination of the electron-tunneling escape time from a GaAs/$Al_xGa_{1-x}As$ quantum well by transient-capacitance spectroscopy

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We show that the tunnel emission of electrons out of a single quantum well into an $Al_xGa_{1-x}As$ conduction band under a perpendicular electric field can be observed by transient-capacitance spectroscopy in the 0.1–100-ms time range. This has been made possible by the use of a semiconductor-insulator-semiconductor-type structure where the GaAs space-charge probe region is separated from the quantum well by a thin $Al_xGa_{1-x}As$ barrier. The variation of the tunneling time with applied electric field is in good agreement with a simple Fowler-Nordheim model. The absolute values of the tunneling time are, however, significantly different from the expected theoretical values. The origin of this discrepancy is briefly discussed.

Recently, much attention has been devoted to the determination of the tunneling time of electrons from a GaAs quantum well (QW) into the continuum of the $Al_xGa_{1-x}As$ conduction band.[1,2] These studies are crucial to the understanding of novel quantum devices such as resonant tunneling diodes, electrically programmable read only memory,[3] quantum-well infrared detectors,[4,5] or modulators.[6] Particularly, as far as those latter devices are concerned, the tunneling of electrons from the QW ultimately controls the charge state of the wells as a function of bias and determines the dark current in infrared detectors.[7] Most of the reported experiments of electron tunneling have been performed by *static* current versus voltage techniques in single barriers (Si/SiO_2,[8] $GaAs/Al_xGa_{1-x}As$,[9] etc.). In these experiments, the relative variations of the tunneling probability with applied electric field is easily obtained and is in good agreement with a simple Wentzel-Kramers-Brillouin (WKB) approach.[10] However, the access to absolute tunneling time is blurred by the complexity of the transport model which takes into account the band bending at the interfaces and the supply function of electrons impinging on the barrier.[11] Kleine *et al.* have reported dynamic measurements of electron emission time from an inversion layer at the $GaAs/Al_xGa_{1-x}As$ interface.[12] However, no absolute tunneling time could be obtained from this experiment because (i) the measurement temperature was high (50–85 K) so that the thermal-related emission was prevailing and (ii) the experiment involved a quasi-Fermi level of electrons and holes which would have made the determination of tunneling time very indirect.

Up to now, these tunneling times have mostly been determined by time-resolved photoluminescence.[2] However, this technique suffers from the fact that many species are involved during the measurement (electrons, holes, and excitons) (Ref. 13) and the time scale cannot be extented above 1 ns because of radiative recombination. For instance, Vodjdani *et al.* have recently shown that hole accumulation in the collector spacer layer plays a major role in the photoluminescence decay time in double-barrier diodes.[14] In this paper, we report *direct* measurements of tunneling times of electrons outside a single quantum well by emission time spectroscopy of capacitance transients or transient-capacitance spectroscopy (TCS). Only electrons are involved in these experiments. The variation of the tunneling times with applied electric field is in good agreement with a Fowler-Nordheim activation mechanism and the preexponential attempt-to-escape time constant is found to be in the 10^{-11}–10^{-12}-s range.

Previous attempts have been reported for the study of electron emission time from QW's by transient-capacitance spectroscopy.[15–17] These experiments are indeed attractive since (i) they deal with only one type of carrier, i.e., the majority carriers electrically injected in the quantum wells, and (ii) they characterize the samples under conditions of field and time scale similar to a real device under operation. In all previous experiments, the GaAs QW's were located in the $Al_xGa_{1-x}As$ barrier space charge region. For thin GaAs wells (<10 nm), no signal related to the electron emission from the quantum wells (either thermal or tunnel) has been detected by the authors. In one case, a transient signal has been observed which has revealed to be unambiguously related to defects near the QW's.[17] We have reproduced these experiments and, indeed, found no signal related to electron emission from a QW level, in accordance with those previous experiments. Although the exact origin of such a lack of signal is still unclear, we believe that the presence of a large density of defects, which are observed in all structures, greatly perturb the injection of electrons in the quantum well and that the capacitance transients are dominated by the electron emission from those deep traps in the $Al_xGa_{1-x}As$ space-charge probe region. In this study we have therefore separated the probe region (the space-charge layer) from the emitting QW. The sample, grown by molecular beam epitaxy, consists in a semiconductor-insulator-semiconductor (SIS) like structure (Fig. 1). A 1.12-μm-thick GaAs layer, Si doped to 1.6×10^{15} cm^{-3} (N_D), is grown on top of a 10^{18}-cm^{-3} Si-

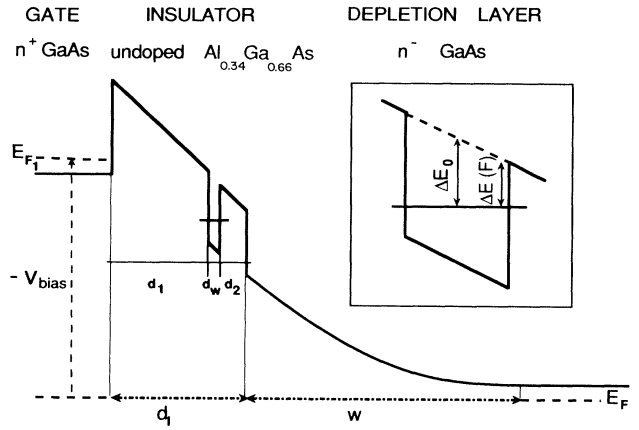

FIG. 1. Energy band diagram of the sample used in this study. The electrons injected in the quantum well during the filling electrical pulse are emitted above or through the $Al_xGa_{1-x}As$ barrier into the GaAs space-charge region. The variation in the density of electrons in the quantum well leads to a shrinkage of the depleted layer and thus to a capacitance transient. The inset shows the barrier lowering due to the applied electric field.

doped GaAs wafer. The insulating region consists of an undoped sandwich of 75.7 nm (d_1) $Al_{0.34}Ga_{0.66}As$, 4.5 nm (d_W) GaAs, and 20 nm (d_2) $Al_{0.34}Ga_{0.66}As$ separating the GaAs QW from the space-charge region. A 280-nm-thick n^+GaAs layer forms the top electrode. These values have been confirmed to secondary-ion mass spectroscopy (SIMS) and high-resolution transmission electron microscopy (HRTEM). Contacts are obtained by Au-Ge-Ni alloying and the final SIS structure is defined using standard photolithographic techniques.

The experiment follows the usual voltage cycle of transient-capacitance spectroscopy.[18] First, the structure is forward biased so that electrons from the GaAs accumulation layer are injected in the $Al_xGa_{1-x}As$ conduction band and captured in the QW. The diode is then reverse biased (polarization V_r) and the trapped electrons are emitted by any mechanism from the QW into the GaAs space-charge region. During emission, the electric field changes at the depleted region surface, the depletion width reduces and thus the capacitance of the device exhibits a transient ΔC related to the surface state charge ΔN in the well by

$$\frac{\Delta C}{C}=\frac{d_2}{W[d_1+d_2+W(\kappa_S/\kappa_I)]}\frac{\Delta N}{N_D}, \quad (1)$$

where W is the depletion layer thickness, κ_S and κ_I are the dielectric constant of GaAs and $Al_xGa_{1-x}As$ (i.e. 12.5 and 11.6 at 4 K), respectively.[19,20] The capacitance change is detected by a fast capacitancemeter (1-μs response time). Using a sampling voltmeter, it has been checked that the transients are reasonably exponential

$$\Delta C=\Delta C_0\exp(-e_n t) .$$

It is thus convenient to use an emission time spectroscopy technique.[18,21] The capacitance signal is detected by a lock-in amplifier with a period P, which is only sensitive to transient signals of rate constant around e_{n0} given by $e_{n0}P=2.51$.[21] In other words, considering the transient signal as a combination of decreasing exponentials (i.e., the Laplace transform), the lock-in output (the TCS signal) is proportional to the component of the combination whose rate is e_{n0}.

Figure 2(a) shows the TCS signal as a function of temperature for an emission rate e_{n0} of 248 s^{-1} and an applied electric field of 7.5×10^4 V/cm in a reverse bias

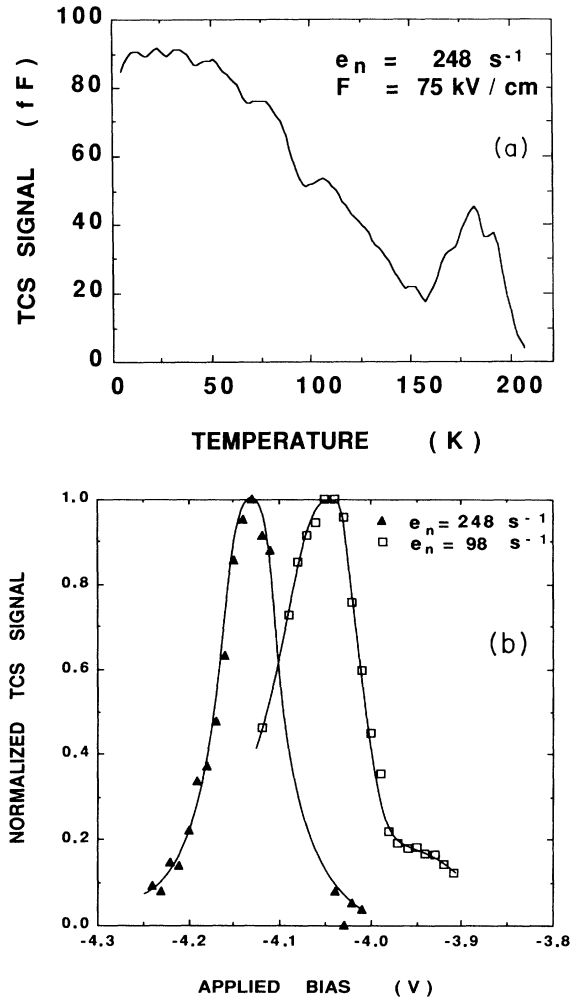

FIG. 2. (a) TCS signal as a function of temperature for an emission rate of 248 s^{-1} and a reverse applied electric field of 7.5×10^4 V/cm. The constant value of the signal at low temperature reveals a nonthermally activated emission mechanism. The peak around 180 K corresponds to the thermal activation of electron emission from a defect center present in the $Al_xGa_{1-x}As$ barrier. (b) TCS signal as a function of reverse bias at 4 K for two emission rates of 98 and 248 s^{-1}. The presence of very sharp peaks which shift to higher reverse bias with increasing emission rate indicates an electric-field-assisted tunneling mechanism.

configuration. From 4 to 60 K, the TCS signal is found to be constant, indicating that the emission is not thermally activated. From 60 to 200 K, the TCS signal decreases. Indeed, because of thermal emission of the carriers above the $Al_xGa_{1-x}As$ barrier conduction band, the transients become faster as the temperature increases so that the emission rate of trapped electrons goes out of the emission rate window e_{n0}. The peak around 180 K has been seen in all our samples, even in $Al_xGa_{1-x}As$ Schottky diodes with no QW's, and corresponds to an activation energy of about 350 meV. The origin of this defect in $Al_xGa_{1-x}As$ is unknown. In order to investigate the low-temperature part of the TCS spectrum, we have studied the variation of the emission rate at a fixed temperature (4 K) as a function of the reverse bias. Figure 2(b) shows the TCS signal as a function of reverse bias for two emission rates of 98 and 248 s^{-1}. The presence of a very sharp peak (width ≈ 100 mV) indicates that the electron emission is highly electric-field activated, clearly revealing a tunneling mechanism. Indeed, while the reverse bias is enhanced, the electric field gets higher at the (GaAs QW)/($Al_xGa_{1-x}As$ barrier) interface. The barrier region gets thinner, thus increasing the tunneling probability (Fowler-Nordheim mechanism).[22] The variation of the peak position for different emission rates allows us to study the electric-field dependence of emission rate e_n as a function of electric field F.

The TCS spectra are thus performed as a function of applied bias for a set of emission rates e_{n0}^i ranging from 36 to 4664 s^{-1}. The position of the peaks indicates the value of the applied bias V^i for which $e_n(F^i)$ is equal to each defined emission rate window e_{n0}^i. The effective electric field F in the GaAs QW is experimentally determined by the Gauss law

$$F=\frac{qN_D}{\epsilon_0\kappa_I}W\ , \tag{2}$$

where q is the electronic charge and ϵ_0 is the vacuum permittivity. The depletion length W is determined by the measured capacitance C through

$$\frac{1}{C}=\epsilon_0 S\left[\frac{\kappa_I}{d_I}+\frac{\kappa_S}{W}\right]\ . \tag{3}$$

The doping concentration N_D and the total insulating barrier thickness ($d_I=d_1+d_2+d_W$), found by fitting the capacitance-voltage curve at the temperature of measurement,[23] are consistent with the values obtained from HRTEM and SIMS measurements. We have checked that possible fixed charges in the $Al_xGa_{1-x}As$ barrier cannot change, in a noticeable way, the value of the electric field in the quantum-well region.

We have thus plotted the values of the electric fields F^i at a peak position for which the emission rate is equal to e_{n0}^i. Figure 3 shows a $\log_{10}e_{n0}$ vs $1/F$ plot. The data are compared with a simple theoretical model. Using the WKB formalism,[10] the tunneling rate of a bound electron through a triangular barrier may be approximated by

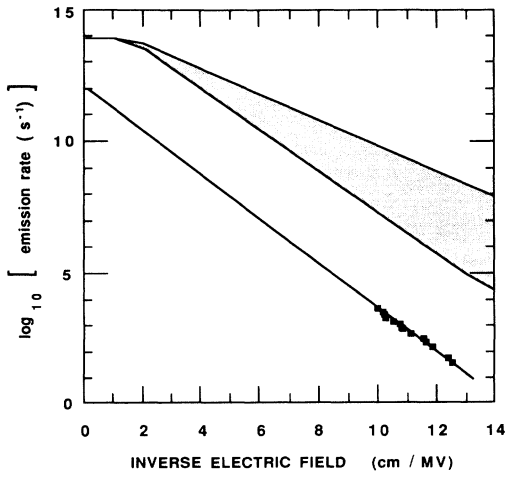

FIG. 3. Electron emission rate e_n from the GaAs quantum well vs the inverse of electric field F. The solid rectangles are the experimental points. The linear dependence of $\log_{10}e_n$ vs $1/F$ is specific to electric-field-activated tunnel emission. The two curves which bound the shaded area are the two extreme Fowler-Nordheim plots taking into account the uncertainties on the effective mass and the barrier height. The best least-squares linear regression of our experimental data is also indicated. Its y-axis intercept yields a value of 10^{-12} s^{-1} for the attempt-to-escape time constant.

$$e_n=\nu_0\exp\left[-\frac{4}{3}\frac{(2m_I^*)^{1/2}}{\hbar}\frac{\Delta E(F)^{3/2}}{qF}\right]\ , \tag{4}$$

where $\hbar$ is the Planck constant, ν_0 is the attempt-to-escape rate and m_I^* is the effective mass of electrons in the $Al_xGa_{1-x}As$ barrier. $\Delta E(F)$ is the energy difference between the QW level and the $Al_xGa_{1-x}As$ conduction band taking into account the barrier lowering due to the electric field (Fig. 1). Equation (4) assumes that the potential barrier is triangular rather than trapezoidal. This should be correct in as much as $Fd_2>\Delta E(F)$, which is *a posteriori* verified. We have made the approximation that ν_0 does not change appreciably in the range of the electric field considered here, 70–100 kV/cm. Moreover, we have neglected the Stark shift, so that $\Delta E(F)=\Delta E_0-Fd_W/2$, where ΔE_0 is the zero-field barrier energy (see inset of Fig. 1). Let us stress that the filling pulse has been optimized so that there is no noticeable variation of the electric field during emission due to the charge state variation of the well. Indeed, the relative variation of capacitance $\Delta C/C$ is less than 4×10^{-4}; that is, according to Eq. 1, $\Delta N<5\times10^9$ cm^{-2}. This leads to a variation of the electric field less than 750 V/cm, which is indeed negligible compared to the applied electric field. The validity of all these approximations has been checked by comparison with the results of a full quantum calculation based on phase-shift analysis.[24]

As indicated in Eq. (4), a linear relationship is thus anticipated between $\log_{10}(e_n)$ and $1/F$. In fact, the relative variation of the slope of the $\log_{10}(e_n)$ vs $1/F$ curve is

given by

$$\Delta E(F)/\Delta E_0 = 1 - Fd_w/2\Delta E_0 ,$$

less than 3% in the investigated experimental range: we have thus neglected this nonlinearity and have taken

$$\Delta E(F) \cong \Delta E(F = 85 kV/cm) .$$

This linear relationship is experimentally verified in Fig. 3 over more than 2 decades of emission rates. As far as the slope of the linear relationship is concerned, two parameters are involved in the fit: m_l^* and ΔE_0. The determination of the effective mass of an electron tunneling through a barrier is still under discussion. We let the uncertainty in m_l^* range from 0.085 to 0.095. The maximum value corresponds to the effective mass of electrons at the $Al_xGa_{1-x}As$ conduction-band edge. The minimum value corresponds to the nonparabolicity correction in the $Al_xGa_{1-x}As$ band gap for the confinement energy in the QW.[25] ΔE_0 is determined by photoluminescence: the $E1$-HH1 transition energy is 1634 meV. Taking into account the growth parameter indications confirmed by the HRTEM results and assuming that 67% of the band offset is in the conduction band,[19] we obtain a value for ΔE_0 of 190 ± 12 meV.

The shaded area shown in Fig. 3 is bounded by the two extreme calculated Fowler-Nordheim curves, taking into account the uncertainties in m_l^* and ΔE_0. The flattening of the curve for small values of the inverse electric field is explained as follows. For very high electric field, the tunneling transparency tends to unity, so that the tunneling rate extrapolates to the attempt-to-escape rate. The experimental value of the slope, obtained by a least-squares linear regression of experimental data in Fig. 3, is found to be 1.7×10^6 V/cm, which is in reasonable agreement with the expected value $[(1.5 \pm 0.2) \times 10^6$ V/cm]. This discrepancy could originate from a slight uncertainty in the doping concentration. The residual difference between the two slopes accounts for a discrepancy of 2 orders of magnitude in the emission rate values at the investigated electric-field range.

In Oppenheimer's formalism,[26] the attempt-to-escape rate is given by the oscillation frequency of the electron on the quantized level, i.e., the Bohr frequency:

$$\nu_0 = (1/d_W)(E/2m_W^*)^{1/2} , \quad (5)$$

where d_W and m_W^* are the QW width and GaAs electron effective mass, respectively. For our structure, ν_0 is 7.6×10^{13} s^{-1}. With the same least-squares analysis of our data, we found a ν_0 extrapolated to $1/F = 0$ between 10^{11} and 10^{12} s^{-1}, which is 2 orders of magnitude lower than the expected theoretical value. The huge value of the uncertainty in ν_0 originates from low emission rates observable with this transient-capacitance technique. Nevertheless, as it appears in Fig. 3, the discrepancy between the theoretical attempt-to-escape rate ν_0 and the Fowler-Nordheim extrapolation of our results is clearly outside experimental uncertainties. Once again, we would like to stress that this cannot be due to uncertainties in m^* or ΔE_0 since (i) all the other physical characterizations (HRTEM, SIMS, C-V curves, photoluminescence) are consistent, and (ii) the experimental Fowler-Nordheim slope is in good agreement with theory.

The origin of this discrepancy cannot originate from the crudeness of the Oppenheimer formalism (i.e., $e_n = \nu_0 T$, where T is the tunnel transparency of the barrier) since, as noticed above, more involved calculations based on the phase-shift formalism[24] lead to very similar theoretical results. We are left to understand why the extrapolated ν_0 is not the Bohr frequency of the electrons on E_1. A possible explanation could be the following. The vibrating electrons in the well are scattered by defects (interface roughness, impurities, etc). Thus, only a small fraction of them have the right wave vector when impinging on the interface, i.e., with a small angle relative to the growth direction. This leads to an effective attempt-to-escape rate largely decreased compared to the pure one-dimensional case. Further study is necessary to confirm this hypothesis.

In conclusion, we show that the emission time of an electron from a quantum well can be directly determined by transient-capacitance spectroscopy. Compared to time-resolved photoluminescence measurements, this method allows one kind of carrier to be involved in the measurement with emission time ranging from the 50- up to 5000-s^{-1} range. This experiment has been made possible by using a particular SIS-like structure which separates the QW from the probe space-charge region. Tunnel emission has been evidenced at low temperature (4–60 K). The variations of the tunneling time with applied electric field are in agreement with a field-activated tunnel mechanism. As far as device applications are concerned, our results confirm that, even at low temperature, quantum wells with usual characteristics as the ones used in this study get emptied in less than 1 ms for an applied electric field in the 10^4–10^5-V/cm range. This is a basic limitation for device such as infrared Stark modulators[6] where such electric fields are usual.

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