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## TIME RESOLVED VERTICAL TRANSPORT IN $GaAs/Al_xGa_{1-x}As$ SUPERLATTICES

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Nous avons étudié la dynamique de transport des porteurs de charge dans une région du super-réseau de  $GaAs/Al_xGa_{1-x}As$  avec un champ électrique. Nous observons les réponses temporelles thermiquement activées du système avec des énergies d'activation dépendant du champ électrique. Nous présentons un modèle d'émission thermo-ionique qui décrit bien les résultats expérimentaux.

We have studied the dynamics of carrier transport in a biased  $GaAs/Al_xGa_{1-x}As$  superlattice region. We observe thermally activated response times with activation energies depending on the electric field and present a thermionic emission model which accurately describes the data.

### Introduction

The transport properties of a semiconductor superlattice (SL) are usually strongly anisotropic. While the high mobilities of the carriers in the plane of such a structure have been investigated extensively [1], only few information is available about the relatively low mobility perpendicular to the layers [2]. Depending on the temperature and on the shape of the barriers and wells in the superlattice, different mechanisms contribute to the electric transport perpendicular to the layers. Tunneling through and thermal activation across the barriers are the most important processes. In this paper we will focus on the dynamics of electronic transport if the latter process dominates. Some time resolved measurements associated with tunneling will be discussed in another contribution at this conference [3].

### Experimental

For the experiments presented here we use a PIN-diode structure with a 100 period (12.5 nm  $GaAs/13.4$  nm  $Al_{0.3}Ga_{0.7}As$ )-SL intrinsic region. The highly doped regions of the PIN-diode consist of a 300 nm  $n^+ - Al_{0.5}Ga_{0.5}As$  layer on the substrate side and a 800 nm  $p^+ - Al_{0.5}Ga_{0.5}As$  window layer followed by a 50 nm  $p^+ - GaAs$  contact layer on the top side. The structure is grown by molecular beam epitaxy on a (100)-oriented  $n^+ - GaAs$  substrate and processed into mesas of  $0.27$  mm<sup>2</sup> active area by photolithographic etching. From capacitance measurements we find a residual doping of about  $10^{16}$  cm<sup>-3</sup> inside the SL-region. The dark current of the samples is  $< 1$  nA.

The experimental setup is similar to conventional time-of-flight experiments [4]. The sample is illuminated using a nitrogen pumped dye-laser (500 ps pulse length, 5 Hz repetition rate) and the photocurrent transients are detected by a TEK 7912AD transient recorder (700 ps rise time). The signal is averaged over several hundred shots and corrected by the dark signal. All measurements are done at temperatures above  $T = 160$  K.

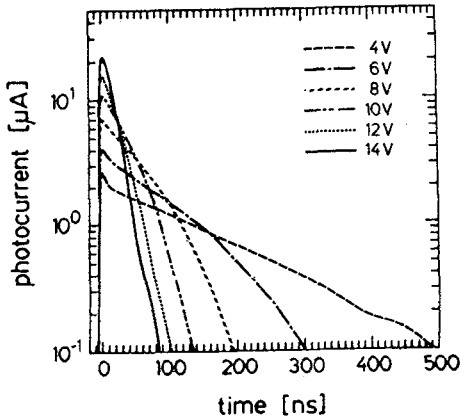


Fig. 1a

Photocurrent transients at a temperature of 200K and different bias voltages.

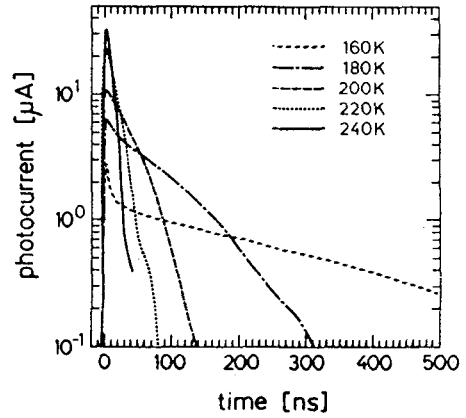


Fig. 1b

Photocurrent transients at a bias voltage of 10V and different temperatures.

Some characteristic photocurrent transients showing the voltage and temperature dependence are presented in Fig. 1. The data were taken at low intensity ( $< 1$  pC collected photocharge per pulse) and at 780 nm wavelength (high penetration depth) to achieve low excitation densities. At higher excitation levels the shape of the transients depends on the intensity of the laser pulse. Excitation with shorter wavelengths gives higher local photo-carrier densities close to the top contact. Under these conditions we observe an intensive fast component (several nanoseconds) which can be related to electron-hole recombination, as the decay time is nearly independent of the applied voltage. In Fig. 1, this component is only visible at low electric fields (Fig. 1a) or low temperatures (Fig. 1b).

The decay of the signal is not purely exponential which can be understood from the theoretical discussion. We obtain an effective response time  $\tau_e$  from a plot of the transient in a doubly logarithmic scale where the slope of the curve becomes minus one at the time  $\tau_e$  by definition. It should be noted that this procedure is exact if the time dependence of the transient is truly exponential. The variation of  $\tau_e$  as a function of temperature is shown in Fig. 2 and is well described by a thermally activated process. A least squares fit to these data results in activation energies systematically decreasing from 157 meV (4V) to 135 meV (14V) with increasing electric fields, corresponding to a lowering of roughly 2.2 meV per Volt applied voltage.

Fig. 3 shows the difference between pulsed and DC-bias which is assigned to band bending effects by space charges: Under pulsed bias condition, the electric field in the intrinsic region due to the applied voltage is constant within a time scale of the dielectric relaxation time. Under DC bias, however, there is an inhomogeneous electric field with a broad spectrum of decay constants. It should be noted that the pulsed bias condition is always satisfied in our experiments as long as the bias voltage is reduced to zero for about 100  $\mu$ s at any time between two consecutive light pulses. This means that the characteristic time constant for the redistribution of charges in the intrinsic region under dark conditions is larger than the time interval of 200ms between the pulses.

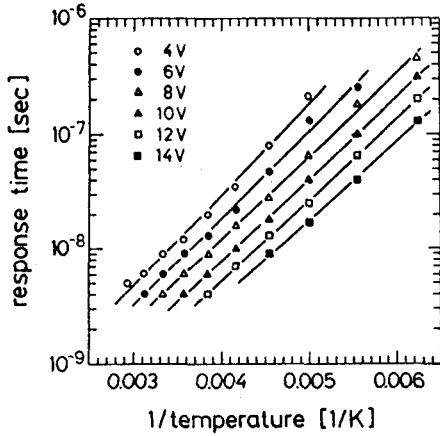


Fig. 2

Temperature dependence of the response time  $\tau_e$  at different bias voltages.

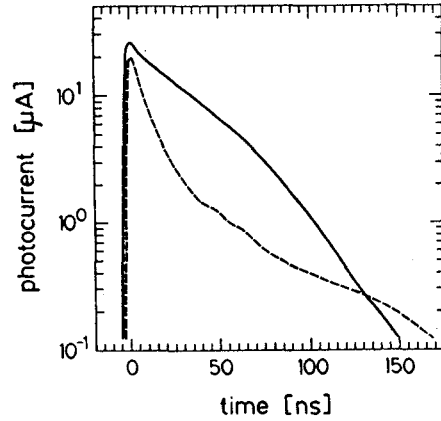


Fig. 3

Photocurrent transients at a temperature of 200K and a pulsed (full line) and DC (dotted line) bias of 10V.

### Thermionic emission model

For a quantitative interpretation of these data we develop a transport model based on standard thermionic emission theory as presented, e. g., in [5,6]. The theoretical description is based on the following assumptions: a.) a 3D-density of states, b.) Boltzmann-statistics, c.) an effective barrier height (neglecting tunneling), and d.) a probability of unity for capturing of emitted carriers by adjacent wells. Assumption c.) is certainly a good approximation for our SL-parameters as long as the electric field is not too high. Assumptions a.) and b.) seem somewhat crude, but they are justified because only states above the barrier height can contribute to carrier transport. From this we deduce transport coefficients giving rise to a Gaussian transport model with effective drift velocity  $v$  and diffusion constant  $D$  :

$$(1) \quad v = \frac{d}{a} \sqrt{\frac{k_B T}{2\pi m^*}} \left( \exp \frac{-\Delta E}{k_B T} \right) \left( 1 - \exp \frac{-q\Delta V}{k_B T} \right)$$

$$(2) \quad D = \frac{d^2}{a} \sqrt{\frac{k_B T}{2\pi m^*}} \left( \exp \frac{-\Delta E}{k_B T} \right) \left( 1 + \exp \frac{-q\Delta V}{k_B T} \right)$$

The parameters are as follows:  $d$ : SL-period,  $a$ : well thickness,  $k_B$ : Boltzmann constant,  $T$ : temperature,  $q$ : elementary charge,  $m^*$ : effective mass,  $\Delta E$ : effective barrier height,  $\Delta V$ : potential drop across one SL period.

From this model it is clear that in the thermionic emission case carrier transport is dominated by the effective barrier height  $\Delta E$  and only weakly dependent on the effective mass itself.

### Comparison with the experiment.

As a first test of the model we insert the measured activation energies into (1). Using  $L/2$  ( $L$ : total thickness of the SL) as an effective drift length, the model actually reproduces the observed response times *within a factor of two*. The variation of the effective barrier height  $\Delta E$  with bias voltage also agrees with a calculated shift of  $\frac{q\Delta V a}{2d}$ , i. e., 2.3 meV per Volt applied voltage, of the lowest electric subband relative to the top of the barrier [7]. The absolute value of the barrier height should be related to the band offset between  $GaAs$  and  $Al_xGa_{1-x}As$ . By linear extrapolation of  $\Delta E$  to zero electric field we obtain a value of about 170 meV between the lowest electronic subband and the top of the barrier. This value seems realistic but we do not believe that the present data can be used for a precise determination of the band offset. A conclusion whether electrons or holes dominate the electronic transport also cannot be drawn from this value due to a possible uncertainty in the actual Al-content of the  $Al_xGa_{1-x}As$  barriers.

A comparison of measured current transients at different excitation wavelengths (= different penetration depths of the light and therefore different initial distributions of electron hole pairs in the SL) with simulations within a Gaussian transport model, however, favours the hypothesis that the measured transients are dominated by the motion of holes. Additionally, we had to assume hole transport to obtain good fits. The diffusion constants obtained by these fits, however, are higher than predicted by eq. (2). This can be attributed to contributions to transport from thermionic emission across more than one barrier.

### Summary

Using a pulsed dye laser system and a fast transient recorder we have studied time resolved vertical transport in a biased  $GaAs/Al_xGa_{1-x}As$  SL region in dependence of wavelength, temperature and electric field. We find thermally activated response times with activation energies depending on the electric field. These response times are very accurately described by a thermionic emission model.

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