Charge-carrier dynamics in GaAs multiple quantum wells determined by contactless photoconductivity measurements

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Charge-carrier dynamics in GaAs multiple quantum wells at room temperature are studied by a microwave conductivity technique with a time resolution of 0.7 ns. It is shown that excess charge carriers decay via a first-order process where the carrier lifetime depends on the layer thickness and doping level.

Charge-carrier kinetics play an important role in the performance of semiconductor devices. These processes can be studied most proficiently by measuring changes of properties directly related to charge carriers (e.g., conductivity or luminescence) upon a variation of the charge-carrier density. Luminescence measurements[1,2] have been successfully applied to study the recombination of excess charge carriers in multiple-quantum-well structures as, for example, the GaAs-$Ga_{1-x}Al_xAs$ structures. As there are promising prospects for the application of this material in lasers,[3] luminescence experiments are the obvious method to characterize this material.

It is difficult, however, to deduce the details of excess-charge-carrier kinetics from luminescence data only. These details may be important for applications in other optoelectronic devices and for fundamental research. Supplementary information can be obtained from photoconductivity measurements. The luminescence reflects the fraction of the excess-charge-carrier population that is subject to a radiative interaction. The photoconductivity reflects the mobile fraction of excess charge carriers. A drawback of conventional photoconductivity measurements is the influence of the contacts. Especially comparison with luminescence data can be rather complicated if contact phenomena have to be taken into account.

In this work a contactless transient photoconductivity method is applied at room temperature to GaAs multiple-quantum-well structures. This time-resolved microwave conductivity (TRMC) method[4] is based on the proportionality between the relative change of reflected microwave power ($\Delta P/P$) upon illumination and the induced conductivity ($\Delta\sigma$):

$$\frac{\Delta P}{P} = A\Delta\sigma \ , \tag{1}$$

where A is a proportionality factor. An additional advantage of this technique is the inherent high time resolution, as there is no influence of the sample capacitance. The time resolution of the TRMC method is governed by the detection equipment, the amplifiers being the limiting components in the present experiments.

The experimental setup is sketched in Fig. 1. Microwaves from a Gunn oscillator operating at 30 GHz are transmitted in a waveguide system via a circulator to the sample. The fraction of microwave power reflected is passed by the circulator to a detector. The rectified signal then is amplified (Hewlett-Packard, model No. 8447D) before entering a digitizer with 500-MHz bandwidth (Tektronix, model No. R7912/7A29). A microcomputer is used for storage and handling of digitized signals and other experimental data, and for operating the Nd:YAG laser (JK Lasers, model AML, YAG is yttrium aluminum garnet) to provide the excitation pulses. This laser uses an acousto-optic loss modular in the resonator to force operation in single longitudinal mode, resulting in the development of a transform-limited pulse during a prelase period. This pulse, which is very accurately defined in terms of both its energy and temporal characteristics, is amplified after Q switching to produce a train of stable mode-locked pulses. From the pulse train a single pulse is selected and amplified to an energy of up to 120 mJ. Fre-

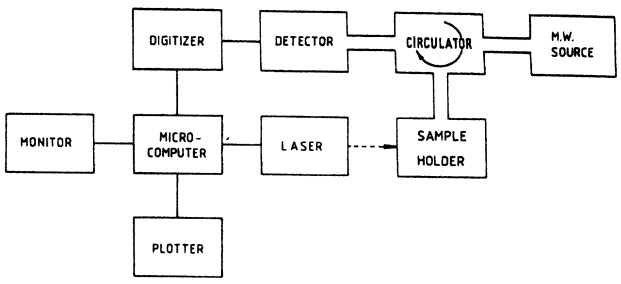

FIG. 1. Experimental equipment to perform contactless photoconductivity measurements.

quency doubling yields 532-nm pulses of up to 70 mJ and a duration of 70 ps full width at half maximum which were used for the present experiments. Specially designed fast ECL (emitter coupled logic) circuitry[5] delivers trigger pulses for the selection of a single pulse, sweeping the digitizer with a jitter of less than 20 ps. So averaging becomes possible without signal deterioration.

The time resolution of the overall system is indicated by the inset of Fig. 2 which shows the response of sample no. 3 (1130B) (see below) to a laser pulse with an energy of 30 $\mu J/cm^2$. The rise time of the conductivity signal is 700 ps in agreement with the digitizer bandwidth.

Full use of the short duration of the excitation pulse and the time resolution of the TRMC method can be made by applying the sampling technique. First experiments resulted in a rise time of 100 ps for the photoconductivity signal.[6]

The GaAs-$Ga_{1-x}Al_xAs$ multiple-quantum-well (MQW) structures were grown by molecular-beam epitaxy as described elsewhere.[7] The MQW systems consist of up to 60 GaAs layers sandwiched between 17.6-nm-thick $Ga_{0.6}Al_{0.4}As$ layers. The thickness L_z of the GaAs layers for each sample is as follows: sample no. 1 (1129B), $L_z = 11.3$ nm; sample no. 2 (1128B), $L_z = 5.2$ nm; sample no. 3, $L_z = 5.5$ nm; samples no. 1 and no. 2 are undoped, whereas no. 3 is p doped by Be with $p = 10^{16}$ cm^{-3} in the wells and the barriers.

The transient photoconductivity of the p-doped sample no. 3 after excitation with a laser pulse is displayed in the main body of Fig. 2. The decay is exponential and characterized by a decay time of 7 ns. In the low-excitation-density range the decay time is independent of this density. Consequently the underlying decay channel must be first order.

Also in the other samples the photoconductivity decays exponentially as can be inferred from Fig. 3 where the fit to a first-order process is indicated by a solid line. The data can be summarized as follows:

(a) The undoped sample no. 1 with the largest L_z shows the largest decay time (17 ns).

(b) The undoped sample no. 2 with a smaller L_z has a shorter decay time (10 ns).

(c) The p-type sample no. 3 with an L_z equivalent to that of sample no. 2 shows the shortest decay time (7 ns).

The first-order decay channel observed in the samples is completely different from the second-order decay observed in undoped bulk GaAs material which is attributed to a band-to-band recombination. This points to decay channels in the MQW structures related to the confinement of charge carriers within these structures. The thermal-equilibrium charge-carrier concentration in our undoped samples is about 10^{14} cm^{-3} which is several orders of magnitude smaller than the excess-charge-carrier concentration produced in the present study (for example, in Fig. 3 a light intensity of 7.5 $\mu J/cm^{-2}$ leads to an excess-charge-carrier concentration of about 10^{17} cm^{-3}) and a first-order band-to-band recombination cannot be expected; consequently this decay channel can be excluded in our MQW samples.

It is improbable that the first-order photoconductivity decay in the MQW samples is due to a recombination at the interfaces because the characteristic time for this pro-

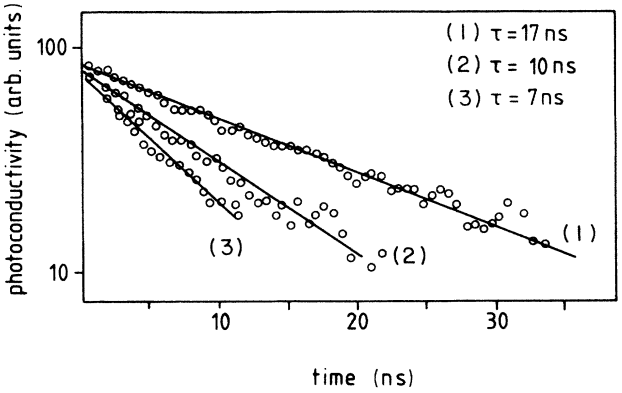

FIG. 3. Photoconductivity transients induced by a 532 nm pulse of 7.5 $\mu J/cm^2$ in different GaAs MQW samples in a semilogarithmic plot.

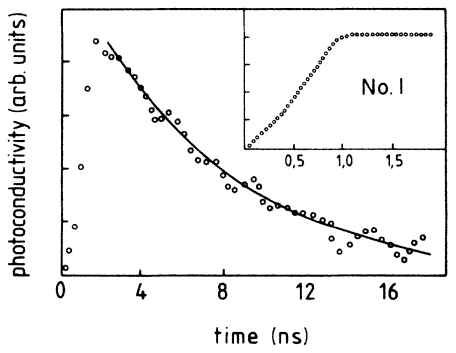

FIG. 2. Photoconductivity transient, induced by a 532 nm pulse of 30 $\mu J/cm^2$. The solid line shows the best fit to an exponential decay with $\tau = 7$ ns. The inset demonstrates the time resolution.

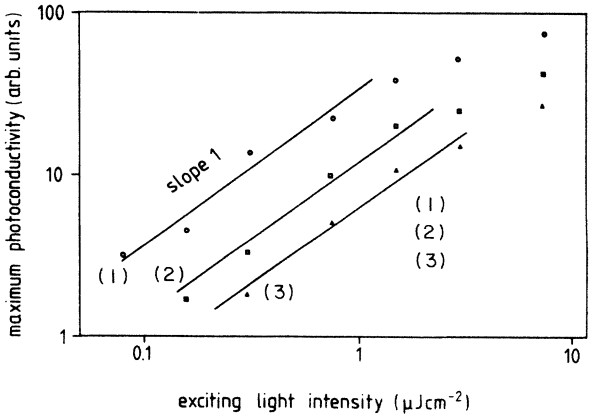

FIG. 4. Dependence of the maximum photoconductivity on the exciting-light intensity.

cess $\tau_s = L_z/(S_1+S_2)$ is larger than the decay times observed in the present experiment: The assumption of an interface recombination velocity of $S_1+S_2<20$ cm/s (Ref. 8) for our high-quality samples leads to $\tau_s > 60$ ns for sample no. 1 and $\tau_s > 30$ ns for samples no. 2 and no. 3.

Recombination via excitonic decay channels as proposed in the literature[2] appears the best explanation. Transient luminescence decay times of the same samples[2] lie in the same order of magnitude and show the same trends as a function of quantum well thickness and doping level as the present photoconductivity data. A detailed kinetic analysis of the luminescence decay in sample no. 1 leads to an excitonic decay time of 15 ns at room temperature.[2] The similarity of this decay time to the decay time of the photoconductivity determined gives additional evidence that the main decay channel in these MQW samples has an excitonic character.

The decreasing carrier lifetime with decreasing L_z can be related to an increased localization of the exciton which increases the recombination probability. p-doping leads to a further reduction of the carrier lifetime which must be attributed to an additional decay channel. The occupation of deeper lying light hole states in subbands by p-doping might cause the additional fast recombination channel. Figure 4 shows the dependence of the maximum photoconductivity on the light intensity for the samples studied.

At intensities higher than approximately 2 μJ/cm^2 the linear dependence of the maximum photoconductivity on the excitation density gives way to a sublinear one. This indicates a second-order process which is operative at high densities on a time scale shorter than the time resolution of the measurements. It is tentative to attribute this process to a band-to-band recombination. A slight increase of the carrier lifetime in all three samples is observed at still higher excitation intensity. Saturation of decay channels could be the reason for this behavior.

In summary, we have shown that contactless time-resolved photoconductivity experiments can provide a different approach to study charge carrier dynamics in GaAs-$Ga_{1-x}Al_xAs$ MQW structures. A detailed analysis of the decay kinetics lies outside the scope of this Brief Report.

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