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In-plane photocurrent spectroscopy in GaAs-AlAs superlattices

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The in-plane photoconductivity of GaAs-AlAs superlattices on GaAs substrates is experimentally studied as a function of the incident photon energy at different temperatures and light intensities. Superlattice and substrate are electrically isolated by a thick $Al_{0.3}Ga_{0.7}As$ barrier but connected through penetrating contacts. Depending on the transport properties of the two subsystems pseudo-negative photoconductivity can be observed, i.e., at the absorption maximum of the superlattice the photocurrent exhibits a minimum. © *1995 American Institute of Physics.*

Photocurrent (PC) spectroscopy is a well recognized method for the investigation of the absorption properties of semiconductor superlattices (SLs). Both parallel[1–10] and perpendicular[11–13] configurations are used. Although, from the technical point of view, photocurrent spectroscopy is a simpler method than absorption measurements, the transport properties of the investigated system turn out to be essential under certain conditions. In the perpendicular case it is known that a maximum in absorption can lead to a minimum in photocurrent, if, e.g., the absorbing intrinsic region of a *p-i-n* diode is larger than both the recombination and the absorption length.[13] In the parallel configuration, mechanisms leading to negative photoconductivity are reported, which include the interaction with deep donor states.[3] In the case of transparent substrates, e.g., in InGaAs-InP or InGaAs-GaAs SLs, true negative PC can occur due to a reduction of the mobility of background carriers via Coulomb scattering[8] or, when the sample is illuminated and contacted from the substrate side, due to the removal of photocarriers from the dominant substrate-related photocurrent by quantum well transitions.[9]

In this paper the appearance of minima in the in-plane PC at absorption maxima is investigated theoretically as well as experimentally. This pseudo-negative PC is found if the SL is separated from the substrate by a very thick barrier, but connected through the contact regions. In this case the lateral photocurrent of the sample is a superposition of the two parallel currents in the SL and the substrate. A simple model for pseudo-negative PC in the parallel configuration is proposed in analogy to the perpendicular case.[13]

The excitation density of carriers in the top system (SL) decreases exponentially as a function of the distance from the surface. The total amount of excited electron-hole pairs in the SL depends on the absorption coefficient α_{SL} of the SL and its thickness W_{SL}. Since the substrate is considered to be infinitely thick, all photons which are transmitted through the SL are absorbed in the substrate. Therefore, an increase of the number of photons absorbed in the SL leads to a complementary decrease of the number of photons absorbed in the substrate. The absorption depends only on the direction of incidence of light z, which is perpendicular to the motion of the carriers x. We have neglected any possible lateral inhomogeneity of the exciting light within the spot. The total intensity absorbed in the SL is

$$I_{SL}=I_0[1-e^{-\alpha_{SL}(\lambda)W_{SL}}] \tag{1}$$

and in the substrate

$$I_{SUB}=I_0 e^{-\alpha_{SL}(\lambda)W_{SL}}, \tag{2}$$

where I_0 denotes the intensity and λ the wavelength of the incident light. Note that both I_{SL} and I_{SUB} depend only on α_{SL} and W_{SL}, since $I_{SL}+I_{SUB}=I_0$.

As the transport properties are generally different in both parts of the sample, a change of absorption in the SL may result in a change of the total current. If the recombination length in the SL is, e.g., shorter than in the substrate, the increase of the current in the SL is smaller than the equivalent decrease of current in the substrate. This effect can lead to a pseudo-negative photoconductivity.

The simple empirical model of photoelectric properties, see e.g. Ref. 13, contains usually Poisson's equation and the transport equation (current density j_n due to drift and diffusion). Furthermore the continuity equation (stationary state) has to be taken into account in the form

$$-\frac{d}{dx} j_n(x)=g(z)-r(x). \tag{3}$$

The generation $g(z)$ and recombination rate $r(x)$ are given by

$$g(z)=\alpha(\lambda)g_0 e^{-\alpha(\lambda)z},$$

$$r(x)=r_0 n(x)p(x),$$

where r_0 and g_0 are constants and $n(x)$ and $p(x)$ denote the electron and hole density, respectively. Note, that in the present case the generation rate depends on z, while the recombination rate is a function of x only. Similar equations are valid for holes. This coupled system (electrons and holes) of nonlinear differential equations can only be solved numerically.

Since the generation rate does not depend on x, the generation rate g_{SL} in the SL and g_{SUB} in the substrate are proportional to I_{SL} and I_{SUB} given by Eqs. (1) and (2). Simplification is achieved by reducing all recombination properties

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to the recombination length L, which decouples the system of differential equations. Solving the continuity equation results in the total current

$$j(\lambda)=j_{SL}+j_{SUB}=g_{SL}L_{SL}+g_{SUB}L_{SUB}. \quad (4)$$

In order to determine the kind of extremum of the photocurrent at a maximum of the absorption, the second derivatives $d^2g_{SL}/d\lambda^2$ and $d^2g_{SUB}/d\lambda^2$ have to be evaluated for $d\alpha/d\lambda=0$. Hence,

$$\left.\frac{d^2j}{d\lambda^2}\right|_{\frac{d\alpha}{d\lambda}=0}=g_0W_{SL}e^{-\alpha_{SL}W_{SL}}(L_{SL}-L_{SUB})\frac{d^2\alpha_{SL}}{d\lambda^2}. \quad (5)$$

In this simple picture, the sign of the second derivative of the current at a maximum of the absorption depends only on the difference between the recombination lengths of the SL and the substrate. If the recombination length of the top system, i.e., the SL, is smaller than that of the substrate ($L_{SL}<L_{SUB}$), a maximum in absorption can result in a minimum of the (total) photocurrent. When the recombination length depends on the carrier concentration, pseudo-negative PC can also occur for $L_{SL}>L_{SUB}$, if the decrease of L_{SL} at an absorption maximum becomes so large that the increase of j_{SL} is smaller than the corresponding decrease of j_{SUB}. For a strong reduction of the mobility, e.g., by Coulomb scattering (cf. Ref. 8), true negative PC can be expected.

Photocurrent spectra were measured on a GaAs-AlAs SL ($L_{GaAs}=5.35$ nm, $L_{AlAs}=3$ nm) embedded by two $Al_{0.3}Ga_{0.7}As$ barrier layers ($d_{top}\approx 0.17$ μm, $d_{bottom}\approx 0.38$ μm) separated from the semi-insulating GaAs substrate by a 0.2 μm buffer layer. In the following we will not distinguish between the buffer layer and the substrate. The contacts consist of In alloyed after scratching the surface under formation gas atmosphere (20% H_2,80%N_2) at a temperature of 450°C. Scratching the surface guarantees that the contacts of both the SL and the substrate are of sufficiently high quality. A measurement on a sample where only the SL was contacted exhibited only maxima in the photocurrent. When SL and substrate are contacted at the same position, pseudo-negative PC is observed for some temperatures. This observation confirms the assumption that this effect is strongly connected with the superposition of the parallel currents in the two subsystems.

The photocurrent spectra were recorded at several temperatures between 20 K and 120 K with a stepwidth of 20 K under different excitation conditions. In the pA region we used a halogen lamp in ac detection mode. The PC spectra were corrected with respect to the lamp spectrum. In the nA region a stabilized Ti:sapphire laser was used in ac detection mode as well as in dc detection mode. The excitation intensity of the laser was about two orders of magnitude larger than that of the lamp.

Figure 1 shows photocurrent spectra for three temperatures (40 K, 80 K, and 120 K) in the ac detection mode excited by the lamp (a) and the laser (b). All of these spectra exhibit clearly the band gap transition (1.63 eV at 120 K) of the SL between the valence band ground state, the first heavy-hole subband (H1), and the first conduction subband (C1) as well as the transition (1.665 eV at 120 K) between the first light-hole subband (L1) and C1. In addition, there is a peak which originates from a broader single quantum well (1.595 eV at 120 K). The H1C1 peak of the SL and of the single quantum well are also detected in photoluminescence. Low excitation results in pseudo-negative PC at 40 K [cf. Fig. 1(a)], while higher excitation already leads to pseudo-negative PC at 80 K. In Table I the results with regard to the extremum of the PC are summarized. Two tendencies are clearly identifiable. Decreasing temperature leads to pseudo-negative PC. Increasing excitation density also leads to pseudo-negative PC. In order to rule out the effect of different excitation geometries, some PC spectra were additionally recorded with the laser at an excitation intensity comparable to that of the lamp. No significant differences were observed with respect to the lamp spectra. In the low excitation regime (lamp) the turning point, where the maxima change into minima, is around 40 K, while at the larger excitation density it occurs around 100 K. In the dc regime the turning point is shifted to a slightly higher temperature. Furthermore, there seems to be a transition back to the normal behavior with decreasing temperature. The low energy peak of the single well, however, remains a maximum for all the experimental conditions given above. In the energy region below the

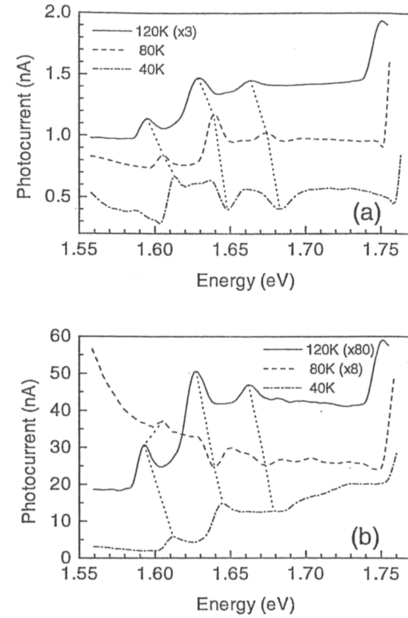

FIG. 1. Photocurrent spectra of the GaAs-AlAs superlattice excited by a halogen lamp in the pA regime (a) and by a Ti:sapphire laser in the nA regime (b). The spectra at 120 K and 80 K are shifted upwards for clarity [in (a): 120 K by 0.9 nA, 80 K by 0.2 nA, in (b): both by 10 nA].

TABLE I. Photocurrent extremum at the H1C1 transition, +: maximum (usual behavior), −: minimum (pseudo-negative behavior), 0: uncertain.

Temperature (K)	Lamp (ac)	Laser (ac)	Laser (dc)
120	+	+	+
100	+	+	−
80	+	−	−
60	+	0(−)	0(−)
40	−	0(+)	0(+)
20	0	0	0

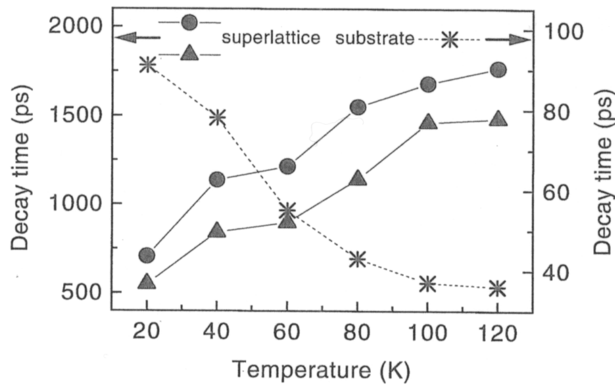

FIG. 2. Decay times of the photoluminescence of the H1C1 transition of the superlattice (solid circles and triangles) and of the substrate (asterisks) as a function of temperature. The excitation intensity of the lower curve (triangles) is one order of magnitude larger than that of the upper one (solid circles).

H1C1 transition, the spectra exhibit a specific behavior in the pseudo-negative PC regime. Usually, the photocurrent increases with increasing energy, while in the pseudo-negative PC regime the PC decreases.

Within our model these results have to be discussed in connection with the recombination lengths of both the SL and the substrate. At higher temperatures the recombination length in the SL is larger than in the substrate ($L_{SL}>L_{SUB}$). The relation between L_{SL} and L_{SUB} changes obviously at lower temperatures. The recombination length becomes shorter in the SL compared to the one in the substrate. Assuming a constant electron velocity in the two subsystems, this means that the recombination times change. Fig. 2 shows the lifetimes of photoexcited carriers in both, the SL and the substrate, as a function of temperature. The lifetimes of the SL are measured at two different excitation intensities (one order of magnitude difference). While the lifetime in the substrate increases with decreasing temperature, the PL decay time in the SL decreases. It follows that the recombination length in the substrate increases, while the recombination length in the SL decreases with decreasing temperature. This observation suggests the existence of a certain temperature range, in which $L_{SL}<L_{SUB}$, i.e., pseudo-negative PC occurs.

The dependence of the recombination lengths on the excitation intensity (larger excitation density is equivalent to shorter recombination time) seems to be a consequence of the fact that the main recombination process is bimolecular recombination of electrons and holes, which depends on the initial intensity. The measurement of the decay times as a function of excitation intensity (see Fig. 2) demonstrates this clear behavior.

In summary, photocurrent spectroscopy in the parallel configuration is a proper method for the investigation of optical properties of semiconductor SLs only, if the SL is isolated from the substrate or it is assured that the recombination length in the SL is large compared to that of the substrate. However, the effect of pseudo-negative PC can be used to investigate the recombination properties of one partial system, if the transport properties of the other system are known.

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