In-plane photocurrent spectroscopy in GaAs-AlAs superlattices

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Photocurrent (PC) spectroscopy is a well recognized method for the investigation of the absorption properties of semiconductor superlattices (SLs). Both parallel\textsuperscript{11-13} and perpendicular\textsuperscript{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.\textsuperscript{13} In the parallel configuration, mechanisms leading to negative photoconductivity are reported, which include the interaction with deep donor states.\textsuperscript{5} In the case of transparent substrates, e.g., InGaAs-InP or InGaAs-GaAs SLs, true negative PC can occur due to a reduction of the mobility of background carriers via Coulomb scattering\textsuperscript{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.\textsuperscript{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.\textsuperscript{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 $\alpha_{SL}$ 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

$$I_{SL} = I_0 \left[ 1 - e^{-\alpha_{SL} W_{SL}} \right]$$

and in the substrate

$$I_{SUB} = I_0 e^{-\alpha_{SL} W_{SL}}$$

where $I_0$ denotes the intensity and $\lambda$ the wavelength of the incident light. Note that both $I_{SL}$ and $I_{SUB}$ depend only on $\alpha_{SL}$ 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

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

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

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

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

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

$$j(\lambda) = j_{\text{SL}} + j_{\text{SUB}} = g_{\text{SL}} L_{\text{SL}} + g_{\text{SUB}} L_{\text{SUB}}.$$  \hspace{1cm} (4)

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

$$\frac{d^2 j}{d\lambda^2} \bigg|_{d\alpha / d\lambda = 0} = g_0 W_{\text{SL}} e^{-\alpha_{\text{SL}}} W_{\text{SL}} (L_{\text{SL}} - L_{\text{SUB}}) \frac{d^2 \alpha_{\text{SL}}}{d\lambda^2}.$$  \hspace{1cm} (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 ($L_{\text{SL}} < L_{\text{SUB}}$), 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 $L_{\text{SL}} > L_{\text{SUB}}$, if the decrease of $L_{\text{SL}}$ at an absorption maximum becomes so large that the increase of $j_{\text{SL}}$ is smaller than the corresponding decrease of $j_{\text{SUB}}$. 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 GaAs-AlAs SL ($L_{\text{GaAs}} = 5.35$ nm, $L_{\text{AlAs}} = 3$ nm) embedded by two $\text{Al}_0.5\text{Ga}_{0.5}\text{As}$ barrier layers ($d_{\text{top}} \approx 0.17$ $\mu$m, $d_{\text{bottom}} \approx 0.38$ $\mu$m) separated from the semi-insulating GaAs substrate by a $0.2$ $\mu$m 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

![Graph](image)

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>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Lamp (ac)</th>
<th>Laser (ac)</th>
<th>Laser (dc)</th>
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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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