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# Photoluminescence from the quasi-two-dimensional electron gas at a single silicon $\delta$-doped layer in GaAs

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Radiative recombination of quasi-two-dimensional electrons with photocreated holes is reported in single silicon $\delta$-doped layers in GaAs. These holes are confined within the GaAs surface and the potential induced by the doping spike, which is repulsive for holes. Replacing the GaAs surface by an $Al_{0.33}Ga_{0.67}As$/GaAs heterointerface the photoluminescence from the $\delta$-doping spike is drastically enhanced. It is shown by photoluminescence and Raman spectroscopy that the density of carriers created by cw photoexcitation can be made sufficiently high in the heterostructure to modify the actual shape of the doping-induced potential well.

So-called $\delta$ (or planar) doping of semiconductor structures has attracted considerable interest because of the possibility of fundamental studies based on $\delta$-doped structures as well as appealing applications in semiconductor devices.[1] An isolated $\delta$-doping spike of, e.g., Si in GaAs represents a quasi-two-dimensional electronic system with the electrons confined in a space-charge-induced potential well. Besides magnetotransport measurements[2-5] and tunneling spectroscopy[6] a number of optical techniques, such as Raman[7,8] and infrared-absorption[9] spectroscopy, have been used to study the electron subbands formed in the doping-induced potential well. Photoluminescence spectroscopy, in contrast, which has been applied successfully to the study of the two-dimensional electron gas formed in modulation-doped single GaAs/$Al_xGa_{1-x}As$ heterojunctions[10-13] has been performed so far only on $\delta$-doped *n-i-p-i* (Refs. 14–16) and *n-i-n-i* (Ref. 8) structures. There is one report of a photoluminescence study of isolated Si doping spikes in GaAs, but no emission related to the quasi-two-dimensional electron gas has been observed.[17] However, it is interesting to apply photoluminescence spectroscopy also to the study of the electron gas at isolated $\delta$-doping spikes which are used, e.g., as building blocks in a number of device structures.[1] Results obtained by luminescence spectroscopy on $\delta$-doped *n-i-n-i* (Ref. 8) and *n-i-p-i* (Refs. 14–16) multilayer structures are not directly applicable to isolated doping spikes because of interactions between carriers localized at individual doping planes in the multilayer systems.

Similar to modulation-doped heterojunctions luminescence spectroscopy of single *n*-type $\delta$-doping spikes is complicated by the fact that the potential confining the electrons is repulsive for the photocreated holes. This reduces the overlap between electron and hole wave functions considerably and therefore the radiative recombination probability is expected to be low. For the photoluminescence spectroscopy of modulation-doped heterojunctions several concepts have been employed to confine the photocreated holes such as a second heterointerface[11-13] or a lightly *p*-type doped $\delta$ spike placed close to the two-dimensional electron gas.[13]

In the present paper we report on a photoluminescence spectroscopic study of single Si $\delta$-doping spikes in GaAs which were placed sufficiently close to the GaAs surface or an $Al_{0.33}Ga_{0.67}As$/GaAs heterointerface to ensure confinement of the photocreated holes. Radiative recombination from the quasi-two-dimensional electron gas is observed in these structures. This recombination is particularly well resolved for excitation with $\simeq 3$ eV photons which are absorbed in the near surface region. It becomes undetectable for excitation below 1.7 eV.

The samples used in the present study were grown by molecular-beam epitaxy (MBE) on undoped semi-insulating (100) GaAs substrates at a sample temperature of 580 °C. A single Si $\delta$-doped layer with an intended dopant density of $8\times10^{12}$ cm$^{-2}$ was placed at a nominal depth $z_0=30$ nm underneath the GaAs surface or the $Al_{0.33}Ga_{0.67}As$/GaAs heterointerface. The $Al_{0.33}Ga_{0.67}As$ layer with a thickness of $z_B=10$ nm was capped by 1 nm of GaAs. The actual depth profile of the Si dopant residing on lattice sites has been determined by *LVM* Raman spectroscopy and shows a strongly asymmetric broadening of $\approx 20$ nm towards the surface.[18] The background *p*-type doping level in the undoped regions of the samples was $10^{14}$ cm$^{-3}$.

The photoluminescence spectra were excited using various lines of a Kr-ion laser. The samples were cooled by He exchange gas in a continuous-flow He cryostate. The emitted light was dispersed in a double-grating monochromator and detected by a cooled intrinsic Ge diode. Raman spectra were recorded using a triple-grating monochromator and multichannel detection by an intensified Si diode array.

Figure 1(a) shows the low-temperature emission spectrum of $\delta$-doped GaAs:Si with the doping spike placed at $z_0=30$ nm underneath the GaAs surface. In Fig. 1(b) the

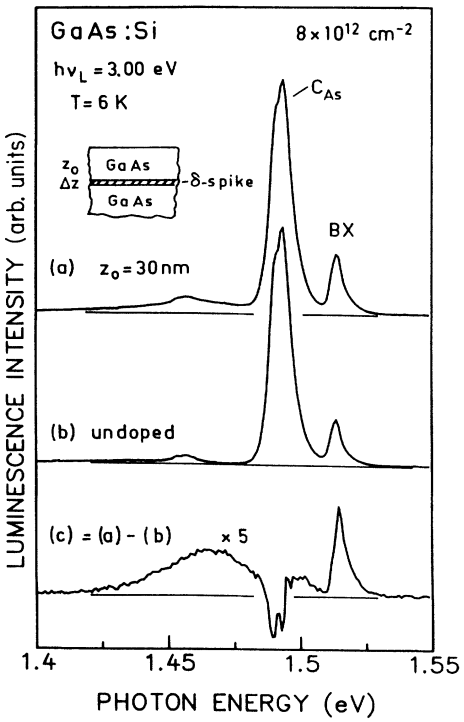


FIG. 1. Low-temperature photoluminescence spectra from (a) $\delta$-doped GaAs:Si with the doping spike placed at $z_0 = 30$ nm underneath the surface and from (b) an undoped reference sample. In (c) the difference spectrum (a) − (b) is displayed magnified by a factor of 5. The spectra were excited at 3.00 eV with a power density of $\approx 1$ kW/cm$^2$. Spectral resolution was 1.5 meV. The sample structure is shown.

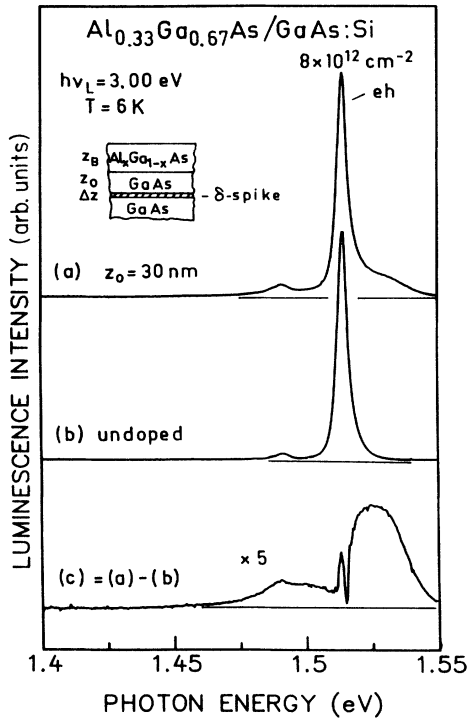


FIG. 2. Low-temperature photoluminescence spectra from (a) a $\delta$-doped $Al_{0.33}Ga_{0.67}As$/GaAs:Si heterostructure with the doping spike placed at $z_0 = 30$ nm below the heterointerface and from (b) an undoped reference sample. In (c) the difference spectrum (a) − (b) is plotted magnified by a factor of 5. The spectra were excited at 3.00 eV with a power density of $\approx 1$ kW/cm$^2$. Spectral resolution was 0.1 meV. The sample structure is shown.

corresponding emission spectrum of a reference sample is displayed where no quasi-two-dimensional electron gas was present. Both spectra were excited at 3.00 eV to minimize the depth of the optical excitation to 20 nm.[19] They are dominated by emission from the undoped GaAs buffer layer with bound excition recombination (BX) at 1.518 eV as well as conduction band and donor to carbon acceptor recombination ($C_{As}$) at 1.493 eV. The corresponding longitudinal-optical (LO) -phonon replica is observed at 1.456 eV. The difference spectrum (a) − (b) in Fig. 1(c) shows a broad band centered around 1.47 eV. The features at $\approx 1.49$ and $\approx 1.52$ eV are artifacts due to the subtraction process.

Figure 2 shows the same sequence of spectra of a $\delta$-doped $Al_{0.33}Ga_{0.67}As$/GaAs:Si heterostructure with the doping spike placed at $z_0 = 30$ nm below the heterointerface. The total emission intensity in this sample is much higher than in the previous case because of the reduced interface recombination velocity compared to the surface recombination velocity of the free GaAs surface.[20] The luminescence spectra Figs. 2(a) and 2(b) are dominated by band-to-band recombination at $\approx 1.518$ eV which indicates a much higher density of photocreated carriers than in the previous case (see below). The difference spectrum Fig. 2(c) shows a well resolved maximum at 1.525 eV and a somewhat weaker shoulder at $\approx 1.49$ eV. The dip at 1.518 eV is an artifact due to the subtraction procedure.

The features resolved in Fig. 2(c) as well as the 1.47-eV band in Fig. 1(c) are assigned to radiative recombination from the quasi-two-dimensional electron gas induced by the $\delta$-doping spike. This assignment is based (a) on the absence of these features in the undoped reference samples and (b) on the fact that this recombination is strongest for excitation with light which is essentially absorbed in the region between the sample surface and the doping spike. For excitation with lower photon energies, which penetrates deeper into the material, the relative intensity of the emission from the electron gas decreases rapidly and is no longer resolved for excitation below 1.7 eV.

The observation of a doubletlike emission in the $\delta$-doped $Al_{0.33}Ga_{0.67}As$/GaAs:Si heterostructure [Fig. 2(c)] can be interpreted by radiative recombination involving two occupied electron subbands. The splitting of $\approx 35$ meV inferred from the luminescence spectrum compares favorably well with the intersubband spacing between the lowest and the first excited electron subband of 35.8 meV measured by electronic Raman scattering on similar structures without $Al_{0.33}Ga_{0.67}As$ capping layer.[21,22] Alternatively the shoulder at $\approx 1.49$ eV might be regarded as a LO-phonon replica of the main peak at 1.525 eV.

The fact that the emission from the quasi-two-dimensional electron gas occurs at slightly different photon energies for the two $\delta$-doped structures with and without the $Al_{0.33}Ga_{0.67}As$ capping layer [Figs. 1(c) and

2(c)] is understood on the basis of the following arguments. On one hand these structures are not identical. The additional $Al_{0.33}Ga_{0.67}As$ layer of 10 nm in thickness may alter the actual shape of the doping-induced potential well. On the other hand for the same excitation power density the number of photocreated carriers is much larger in the heterostructure due to the reduced interface recombination velocity.[20] Upon variation of the excitation power density the emission energy remains fixed for the GaAs:Si $\delta$-doped structure. But in the $Al_{0.33}Ga_{0.67}As$/GaAs:Si heterostructure this emission shows an energy down-shift with decreasing power density towards the emission energy observed for the structure without $Al_{0.33}Ga_{0.67}As$ capping layer. The present energy shift is similar to luminescence peak shifts reported for $\delta$-doped *n-i-p-i* structures excited with varying power densities.[15,16]

The above finding, that the emission energy and consequently also the actual shape of the potential well confining the electron gas can be modified by optical excitation in the $\delta$-doped structure with $Al_{0.33}Ga_{0.67}As$ capping layer gets support from Raman spectra of coupled phonon-plasmon intersubband modes. For excitation at 3.05 eV in resonance with the $E_1$ band gap of GaAs scattering by intersubband plasmon-phonon modes is strongly enhanced in the present $\delta$-doped GaAs structures.[21] Such low-temperature Raman spectra are displayed for the structures without and with the $Al_{0.33}Ga_{0.67}As$ capping layer in Figs. 3 and 4, respectively. The scattering configuration was $x(y,y)\bar{x}$ where $x$, $y$, and $z$ denote (100) crystallographic directions. Besides scattering by up to three GaAs LO phonons and by the AlAs-like LO phonon ($LO_2$) in the $Al_{0.33}Ga_{0.67}As$ capping layer (Fig. 4) two intersubband plasmon-phonon modes labeled $\omega_A^*$ and $\omega_B^*$ are observed. They arise from transitions involving the lowest ($\omega_B^*$) and higher-lying subbands ($\omega_A^*$), respectively, which couple to collective plasmon modes of the quasi-two-dimensional electron gas.[21] Increasing the excitation power density from 0.1 to 8 kW/cm$^2$ there is almost no change in the Raman spectrum from the structure *without* $Al_{0.33}Ga_{0.67}As$ capping layer except for a slight frequency down-shift of the $\omega_B^*$ mode. For the structure *with* $Al_{0.33}Ga_{0.67}As$ capping layer the spectra excited with power densities up to $\approx 1$ kW/cm$^2$ are essentially the same as for the uncapped sample [Figs. 4(b) and 4(c)]. Only the relative intensities of the $\omega_A^*$ and $\omega_B^*$ modes are decreased due to additional attenuation in the capping layer. For the highest power density of 8 kW/cm$^2$, however, the spectrum changes considerably [Fig. 4(a)]. The $\omega_B^*$ peak broadens and shifts to higher frequencies and a broad background from electronic Raman scattering appears which shows a Fano-type interference with the one-LO-phnon line.[23] This spectrum resembles very much the one observed for $\delta$-doped GaAs:Si where the doping spike has been placed so close to the surface (e.g., $z_0 = 10$ nm) that no confined electron subbands are resolved anymore.[21]

We interpret the change in the Raman spectrum from the $\delta$-doped structure with $Al_{0.33}Ga_{0.67}As$ capping layer observed for the highest power density by a modification

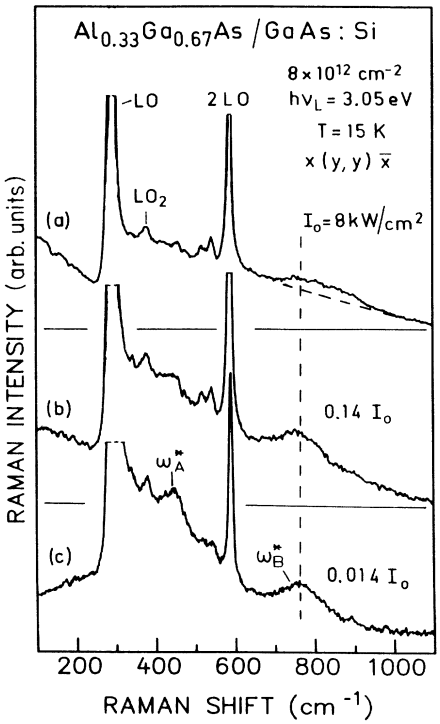


FIG. 4. Low-temperature Raman spectra from a $\delta$-doped $Al_{0.33}Ga_{0.67}As$/GaAs:Si heterostructure with the doping spike placed at $z_0 = 30$ nm below the heterointerface. The spectra were excited at 3.05 eV with various power densities indicated. Spectral resolution was 8 cm$^{-1}$.

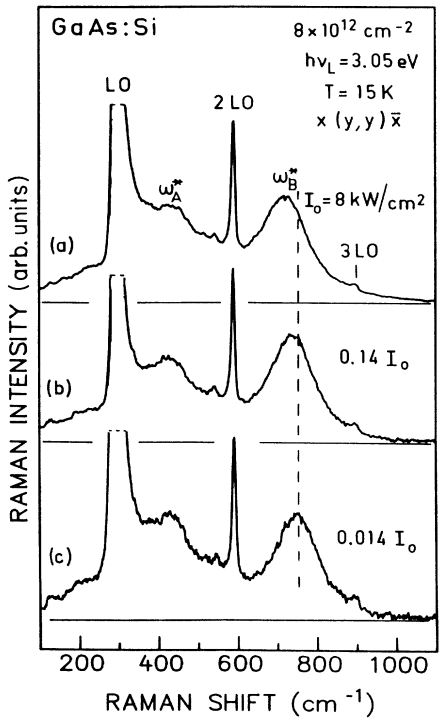


FIG. 3. Low-temperature Raman spectra from $\delta$-doped GaAs:Si with the doping spike placed at $z_0 = 30$ nm underneath the surface. The spectra were excited at 3.05 eV with various power densities indicated. Spectral resolution was 8 cm$^{-1}$.

of the actual shape of the doping-induced potential well due to photocreated carriers. These carriers provide additional charges for the screening of the ionized donors and therefore tend to flatten the potential well. The increase in energy of the $\omega_B^*$ mode can be taken as an independent proof for an increase of the total electron density. This is because the bare subband spacing is expected to be reduced upon reduction of the depth of the potential well. Consequently the depolarization shift and therefore also the free-carrier concentration has to increase for high excitation power densities.[24] A more quantitative analysis of the collective mode spectra is complicated by the occupation of several subbands in the present structures.

In conclusion we have observed radiative recombination of electrons in the quasi-two-dimensional electron gas formed in Si $\delta$-doped GaAs. For sample structures capped by an $Al_{0.33}Ga_{0.67}As$ layer the density of carriers created by cw photoexcitation has been shown to be sufficiently high to modify the actual shape of the doping-induced potential well. The observation of emission from the quasi-two-dimensional electron gas in single $\delta$-doped layers in GaAs opens the possibility to study such structures by photoluminescence and related techniques, such as, e.g., magnetoluminescence spectroscopy.

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[22]The direct measurement of the subband splitting in the $Al_xGa_{1-x}As$ capped structure by electronic Raman scattering with excitation in resonance with the $E_0+\Delta_0$ band gap is not possible. This is because of the strong enhancement of the radiative recombination across the $E_0+\Delta_0$ gap in this structure masking completely the Raman spectrum.

[23]See, e.g., G. Abstreiter, M. Cardona, and A. Pinczuk, in *Light Scattering in Solids IV,* edited by M. Cardona and G. Güntherodt (Springer-Verlag, Berlin, 1984), p. 127.

[24]See, e.g., A Pinczuk and G. Abstreiter, in *Light Scattering in Solids V,* edited by M. Cardona and G. Güntherodt (Springer-Verlag, Berlin, 1989), p. 153, and references therein.