# Single (In,Al,Ga)As quantum dot micro-photoluminescence at high surface density of dots – a possible role of Mn doping

**T. Słupiński, J. Suffczyński, J. Papierska, W. Pacuski, J. Borysiuk, R. Bożek**
*Faculty of Physics, University of Warsaw, Pasteura 5, Warsaw, Poland*

Quaternary type (In,Al,Ga)As/(Al,Ga)As quantum dots (QD) allow to extend the emission wavelength range to the red light from infrared proper to InAs/GaAs QDs mostly studied so far. Independently, quaternary compounds allow, in a wide range, to vary the strain which is an origin of quantum dots nucleation in epitaxial growth. Thus (In,Al,Ga)As offer a wide range of parameters which can be controlled for studies of formation and properties of QDs, including bandgap and strain engineering [1].

In this work, we report on the observation of single QD emission in micro-photoluminescence (μ-PL) of $In_{1-y}(Al_xGa_{1-x})_yAs$ QDs embedded in $Al_xGa_{1-x}As$ barriers (e.g. $x = 0.75$ and $y = 0.6$) prepared by MBE on GaAs (001) $2^o$ off-oriented substrates. μ-PL revealed well-separated sharp emission lines of half-width above 100μeV in (In,Al,Ga)As in the spectral range 660-900nm depending on compositions $y$ and $x$. Unexpectedly, sharp emission lines, having features of the single QD emission (exciton, bi-exciton, charged exciton were identified), have been observed for a high surface density of $In_{1-y}(Al_xGa_{1-x})_yAs$ QDs ($10^{10} \div 3 \cdot 10^{11}$ dots/cm$^2$, deposition thickness equal to the critical thickness for a nucleation of dots $h_{crit} + (1 \div 2)$ monolayers) and which were doped with Mn (several Mn atoms/dot). This is in contrary to a common belief that single dot emission lines can be observed solely for a low surface concentration of dots. We discuss possible mechanisms of observation of sharp emission lines at such high QD densities: (i) an influence of Mn doping on suppressing the emission from large fraction of dots, (ii) a role of enlarged exciton or carriers diffusion length in case of overlapped dots and, consequently, a possibility for excitons to recombine in a small fraction of dots favored radiatively or energetically, (iii) a photonic enhancement of emission from some dots, related to lateral patterns apparently formed by self-organized dots at their high surface densities visible by atomic force microscopy (AFM), (iv) a suppression of radiative recombination from large fraction of dots around dislocations or other defects which may be formed at high dot density [2].

The critical thickness for a nucleation of dots, determined by RHEED 2D/3D transition time in MBE, which scaled as $h_{crit} \sim \varepsilon_{//}^{-1.6}$ with in-plain misfit strain changing $y$ in $In_{1-y}(Al_xGa_{1-x})_yAs$, is consistent with the strain picture of surface dots formation and supports the notion that quaternary (In,Al,Ga)As dots are formed due to strain, similar like InAs dots. AFM studies of dots which were grown and left uncovered on the sample surface were used to estimate the surface density of dots, assuming that both layers of dots – uncovered one on sample's surface or embedded one in (Al,Ga)As barrier - have comparable densities of dots, as suggested by very similar nucleation critical thicknesses observed by RHEED 2D/3D transition. Also, cross-sections were studied by electron microscopy (TEM). μ-PL measurements vs excitation power for charged excitons revealed quadratic type dependence, which can be interpreted as related to effective electric charging of quantum dots, and indicate either a presence of Mn acceptors in dots or lightly n-type (low $10^{16}$ cm$^{-3}$) (Al,Ga)As barriers.

[1] T W Schlereth, C Schneider, S Höfling and A Forchel, *Nanotechnology* **19**, 045601 (2008)
[2] R. Kuszelewicz, J.-M. Benoit, S. Barbay, A. Lemaître, G. Patriarche, K. Meunier, A. Tierno, and T. Ackemann, *J. Appl. Phys.* **111**, 043107 (2012)

Research is supported by NCN (Poland) grant No 2012/05/B/ST7/02155.