Optical properties of (In,Ga)As Nanowire arrays on Silicon


aWalter Schottky Institut and Physik Department, bInstitute for Advanced Study, and cInstitute for Nanoelectronics, all at Technische Universität München, Garching, D-85748, Germany

Gregor Koblmüller: From 2001-2004, G. Koblmüller was a Graduate Student Researcher at Infineon Technologies, Corporate Research, and received a Dr. Tech. in Technical Physics, Technical University Vienna in 2005. From 2005 and 2008, Dr. Koblmüller worked at UC Santa Barbara’s Materials Department as a Postdoctoral Research Associate and later as an Assistant Project Scientist. In 2009, Dr. Koblmüller joined the Walter Schottky Institute, Technical University Munich as Group Leader in III-V Materials, Staff Scientist and Lecturer.

Dr. Koblmüller is the recipient of the Young Investigator MBE Award (Intl. MBE Conference, Berlin, 2010); Marie Curie International Reintegration Grant (2009); and IUPAP Young Author Best Paper Award (ICPS, Vienna, 2006).

Group-III arsenide nanowires (NW) exhibit significant potential to drive new applications in nano-electronic and photonic devices especially when integrated on low-cost silicon (Si) platform. In particular, (In,Ga)As-based NWs and their heterostructures are of great interest due to their wide functionalities in NW field effect transistors, light absorbers and emitters covering a large infrared (IR) spectral region. Here, we report recent highlights on the growth and optical properties of site-selective, catalyst-free (In,Ga)As NW arrays on Si (111) substrate. Using a combination of nanoimprint lithography (NIL) for large-scale pre-patterned Si (111) templates and subsequent high-purity molecular beam epitaxy (MBE), spontaneous non-catalytic growth of (In,Ga)As NWs (free of foreign or self-catalysts [1,2]) was realized with very high-yield (> 98%) periodic vertical NWs and pristine non-tapered morphological homogeneity. Remarkable NW size variation was achieved for the underlying selective area epitaxy (SAE) growth process by a variety of methods: e.g. (i) tuning of the interwire distance (i.e., via self-limited growth) [3,4], (ii) modification of growth parameters [5], or (iii) variation of composition (i.e., In1-xGaxAs) [6].

Based on the finely tuned aspect ratios we investigated the largely unexplored optical properties of these NWs using low-T photoluminescence (PL) spectroscopy. First, for binary InAs with a wurtzite (WZ) dominant crystal structure the main contributions to the emission spectra are determined as a function of aspect ratio, giving dominant emission from direct band-edge (~ 0.41 eV) and from the surface Fermi edge (~0.43-0.44 eV). Interestingly, a cross-over between these two competing recombination mechanisms is found near a critical NW diameter of ~ 100 nm, while quantum confinement effects start playing a role only for very thin NWs (~ 30 nm) [7].

In addition, we report on the emission properties of composition-tuned In-rich In1-xGaxAs NWs and show how through careful growth optimization the Ga content can be varied over a large band gap and wavelength region. Interestingly, we found that the PL linewidths are as narrow as 29 – 33 meV (measured for ensembles of >10^3 NWs), which is independent of the Ga content. This remarkable finding is attributed to the superiority of SAE growth on NIL-Si (111) substrates giving very low degree of phase separation. In contrast, self-assembled, spatially uncorrelated In1-xGaxAs NW arrays show larger compositional inhomogeneity with increased peakwidths in 2θ–ω high-resolution x-ray diffraction scans as well as broadened Raman modes [6].

Moreover, due to the periodicity of the homogeneous (In,Ga)As NW arrays their optical properties are further very sensitive to the direction of incident excitation, i.e., no PL emission was observed by excitation under normal incidence to the sample surface. This indicates that light emission is preferentially into guided photonic bands with higher 2D photonic mode density in the plane as opposed to the plane perpendicular to the surface. These findings open new avenues for well-controlled bottom-up photonic crystal cavity designs, where some of these prospects will be discussed.

*Gregor.Koblmueller@wsi.tum.de; phone +49 89 289-12779; www.wsi.tum.de
Fig. 1. (a) Photograph (upper panel) and top-view FE-SEM image (lower panel) of a site-selectively grown In$_{1-x}$Ga$_x$As NW array on NIL-SiO$_2$/Si (111) with a ($\phi^{Ga}_G/\phi^{In+}_S$) ratio = 0.1; (b-d) Close-up FE-SEM images in bird’s eye view of the same In$_{1-x}$Ga$_x$As NW array as viewed in (a), and In$_{1-x}$Ga$_x$As NW arrays grown under different ($\phi^{Ga}_G/\phi^{In+}_S$) ratio of 0.3 (c) and 0.5 (d).

Fig. 2. Low-T (20 K) PL spectra of several composition-tuned site-selective In$_{1-x}$Ga$_x$As NW arrays on NIL-SiO$_2$/Si (111), as measured from NW ensembles (excitation power = 156 mW). PL spectra are normalized to the respective spectrum of binary InAs NWs [x(Ga) = 0] with x(Ga) values as quantified by XRD. Note that the PL linewidths are independent of x(Ga).

Keywords: nanowires, InGaAs, III-V photonics on Si, photoluminescence, optical properties, bottom-up photonic crystal array, molecular beam epitaxy