III/V Nano-Ridge Engineering for Device Integration on 300 mm Silicon

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Abstract **Nano-ridge Engineering (NRE) is a novel integration approach for III/V devices on 300 mm Si wafers. It starts with selective area growth (SAG) inside narrow trenches to reduce the misfit defect density by aspect ratio trapping (ART). The growth is prolonged outside of the trenches and the nano-ridges (NR) are engineered towards an increased NR volume and a broad (001) top-surface beneficial for the integration of heterostructures. The device specific NR shape designing is called NRE, which implies the manipulation of the growth rate hierarchy on the different NR facets. In a first laser device demonstration, an InGaAs/GaAs multi-layer stack was embedded into a GaAs NR which acts as a waveguide. Optically pumped laser operation emphasizes the achieved high crystal quality. Recently the emission wavelength of 1020 nm was extended to 1300 nm using an In20%GaAs NR. Increasing the NR volume even more allows for the integration of a heterojunction bipolar transistor (HBT) on Si. A double-oxide pattern was applied to reduce sidewall deposition in the junction area. The HBT device performance on Si is very comparable to a reference structure deposited on a GaAs substrate, which shows the tremendous potential of NRE for various III/V device integration on Si.**

Keywords **III/V integration on Si, monolithic integration, laser diode, heterojunction bipolar transistor (HBT)**

NRE [1, 2] is a new approach for the monolithic integration of III/V devices on Si. It is based on SAG by metal organic vapor phase epitaxy (MOVPE) using Si substrates with a nano-scaled Si/SiO_2 trench pattern. The high aspect ratio of the trenches (height/width) guarantees an efficient blocking of the misfit defects via ART which are introduced by the lattice mismatch between III/V and Si. The heteroepitaxial growth is continued out of the oxide trenches in order to clearly increase the III/V volume and to engineer a specific nano-ridge (NR) shape required for III/V device integration.

As the III/V NRs behave as perfect waveguides, the first device demonstration was an optically pumped distributed feedback (DFB) NR laser [3]. InGaAs/GaAs multi-quantum wells are embedded as an active material into the GaAs NR whereas an InGaP cap layer reduces surface recombination and improves the carrier confinement, see figure 1 a)-c). A DFB grating was patterned on top of the NR to create the optical feedback required for lasing. The nano-scale dimension of the III/V NRs together with their vicinity to the Si layer would allow evanescent coupling of the laser light to a Si/SiO_2 waveguide, a concept being clearly beneficial for photonic integrated circuits (PICs). Optimizing the design enables an efficient light coupling with decent coupling length and larger tolerance in the fabrication process [4], see figure 1 d). Currently the growth of p-i-n junctions is explored to realize an electrical pumped laser and photodetector, see figure 1 f). Increasing the NR size makes it also possible to integrate an HBT device on Si [5], which requires more active area for a high current. In this case a double-oxide pattern was designed to reduce sidewall deposition. Therefore, the growth conditions of the sub-collector were chosen in such a way that the NR, evolving on top of the 1st trench oxide, broadens quickly to touch the 2nd oxide ensuring that the deposition of the collector, base and emitter is 2-dimensional. Figure 2 a)-c) illustrates the HBT integration method based on a pattern with two oxide layers. The performance of these first monolithic integrated devices is very similar to a reference HBT structure deposited pseudomorphically strained on a native 2 inch GaAs substrate. Figure 3 a) holds a summary of TEM investigations of the full device structure and figure 3 b) shows the Gummel plot comparing the heteroepitaxial and homoepitaxial HBT devices [5].

These first device examples emphasize the potential of NRE for III/V device integration on Si. It is self-evident that these concepts can be extended to modulators, amplifiers, imagers and HEMTs on Si. At present, NRE of GaSb, InP as well as of InGaAs is explored for different In-contents to widen the range of NR device application. Lately, optically pumped lasing even at 1300 nm was demonstrated based on InGaAs NRs with 20% In, see figure 1 e). The key criterium for a successful NR device integration on Si is to minimize the misfit defect density in the active region. But the whole integration concept as well as process flow must be carefully optimized, taking into account the nano-scale dimension of the device and the impact of a large surface area.

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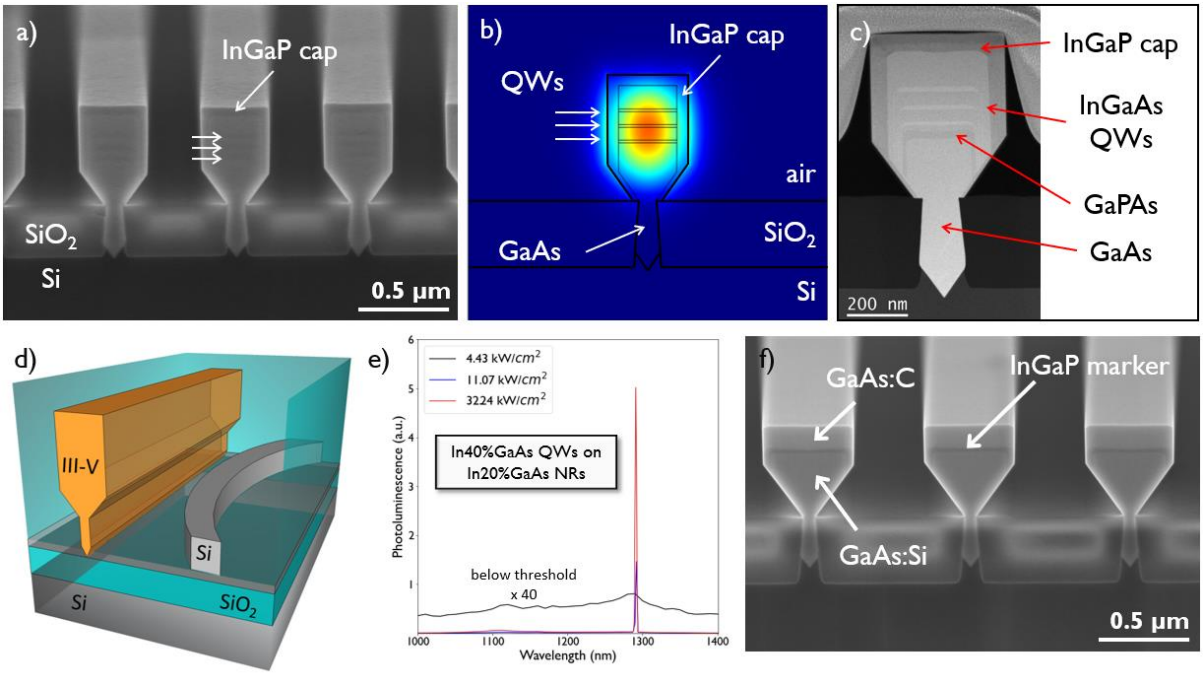

Fig. 1. a) Tilted cross-section SEM (scanning electron microscopy) image of an In20%GaAs/GaAs multi-quantum well NR laser array. b) Profile of the fundamental TE-like optical mode supported by a NR waveguide. c) High angle annular dark field scanning transmission electron microscopy (HAADF-STEM) image of a NR laser [1]. d) 3D sketch of an advanced adiabatic coupler [3 4]. e) Spectra of an optically pumped In20%GaAs NR laser with In40%GaAs quantum wells (QWs) as an active area for different pump intensities. d) Tilted SEM image of a NR p-n-junction.

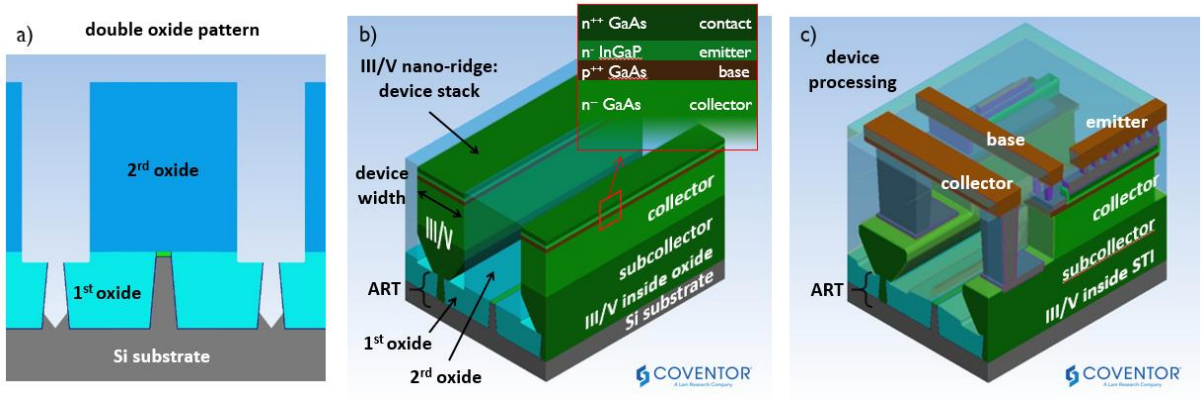

Fig. 2. a) and b) Sketch of the double oxide pattern and the integration of the HBT heterolayer stack. c) illustration of the final integration approach on a 300 mm Si substrate [5].

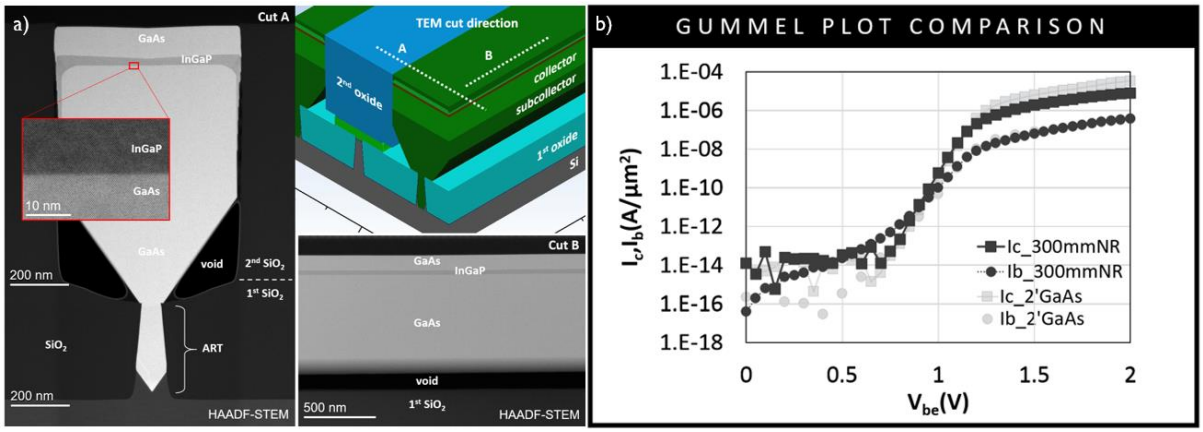

Fig. 3. a) HAADF-STEM images of the whole HBT device in both cut directions [5]. b) Gummel plot of the heteroepitaxial HBT on 300 mm Si and of a homoepitaxial reference sample deposited on a 2 inch GaAs substrate [5].