Embedded HSQ Nanostructures in GaAs Homoepitaxy by MOCVD and MBE

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Embedded dielectric micro/nanostructures remain an active area of research with a wide range of potential applications in quantum photonics, integrated circuits, and metasurfaces. Understanding the interaction of fabrication techniques for embedded structures and epitaxial growth details are critical to their design and use. This work explores homoepitaxial GaAs over HSQ nanoscale grids patterned by electron beam lithography (EBL). HSQ cured by EBL exposure and subsequent development is converted to a network structured silicon oxide. Patterning HSQ to produce nanoscale dielectric structures enables production of higher fidelity nanostructures than approaches using large-area deposition and patterned etching. A single lithography step, without further pattern transfer, also minimizes process complexity and risk of growth chamber contamination. HSQ grid structures consisting of high aspect ratio (80 nm x ~20 nm) "nanowalls" were patterned by EBL on (100)-oriented GaAs wafers off-cut 6° toward the nearest (111)A. As shown in Figure 1, a square grid design with 10 μm spacing, oriented along the $[011]$ and $[0\bar{1}1]$ crystal directions, was used. 1 μm thick homoepitaxial growths were subsequently performed on the nanopatterned substrates by both molecular beam epitaxy (MBE) at 550°C, 610°C, and 680°C with a V:III ratio of 14, and by metal-organic chemical vapor deposition (MOCVD) at 650°C with a V:III ratio of 50; comparative growths using on-axis substrates were also performed via MOCVD. The resultant epilayers were analyzed by high resolution scanning electron microscopy (HR-SEM) and atomic force microscopy (AFM).

The specific orientation of HSQ nanowalls had the most significant impact on local epilayer morphology for both MBE and MOCVD growths. Interestingly, as shown in Figure 2, the two growth methods yielded effectively opposite effects, with vast differences in epitaxial wetting, growth initiation/inhibition, overgrowth, and type/number/propagation/direction of material imperfections. For both on-axis and off-cut substrates, the MOCVD growths possess highly faceted trenches along the [011] direction that extend down to the substrate surface; no GaAs growth is observed over or adjacent to the HSQ lines. In the opposite direction, along the $[0\bar{1}1]$, the growth yielded shallow, smooth trenches above the HSQ for 6° off-cut substrates, as shown in Figure 3, and smooth overgrowth for on-axis. The initial indication is that MOCVD-grown GaAs does not wet the $[011]$-oriented HSQ lines, with resultant faceting preventing coalescence. However, the $[0\bar{1}1]$-oriented lines appear to impact growth only mildly for the off-cut substrates, with little effect for on-axis. In the MBE-grown material at our standard growth temperature (610°C), the result is heavy, jagged faceting in the opposite direction than that of MOCVD, or $[0\bar{1}1]$, with the orthogonal yielding full overgrowth with no observable faceting or growth inhibition. However, under non-standard MBE temperatures (550°C and 680°C) faceted trenches form equally along both <011> directions. The striking differences between the MBE and MOCVD epilayers highlight the differences in the growth techniques themselves and the interaction with foreign materials, including the role of directional surface diffusion and reactive surface chemistry.

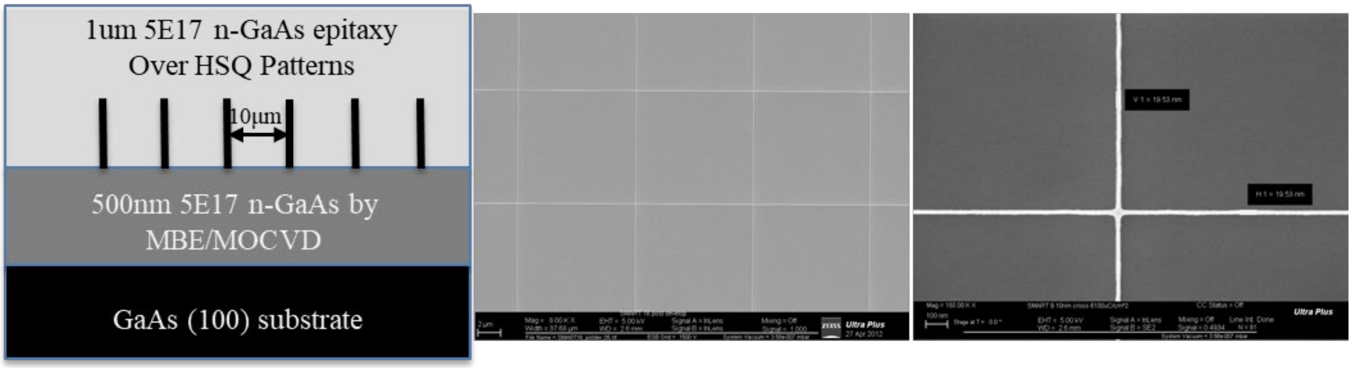

Figure 1. a) Schematic of epitaxial structure with embedded HSQ nanowalls (schematic not to scale) and SEM images b)8000x magnification c) 150,000x magnification of as-developed HSQ patterns 80 nm tall x ~20 wide with a 10 μm grid spacing.

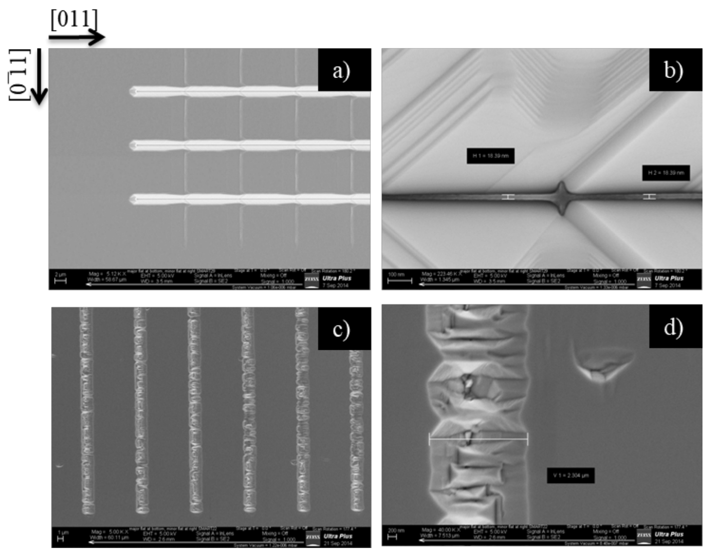

Figure 2. SEM images after 1 μm GaAs homoepitaxy on 6° off-cut substrates by **a-b)** MOCVD at 650°C with a V:III ratio of 50 **c-d**) MBE at 610°C and V:III ratio of 14. Image **b**) shows that in the MOCVD material the HSQ line is visible at the bottom of the GaAs well along [011], appearing to have no GaAs growth on top of the HSQ. Additionally in **b)**, the intersection of the HSQ grid is visible on the substrate with the GaAs overgrowth only over the vertical $[0\bar{1}1]$-oriented HSQ line. The MBE growths, **c-d,** show faceted imperfections in the opposite direction as those for

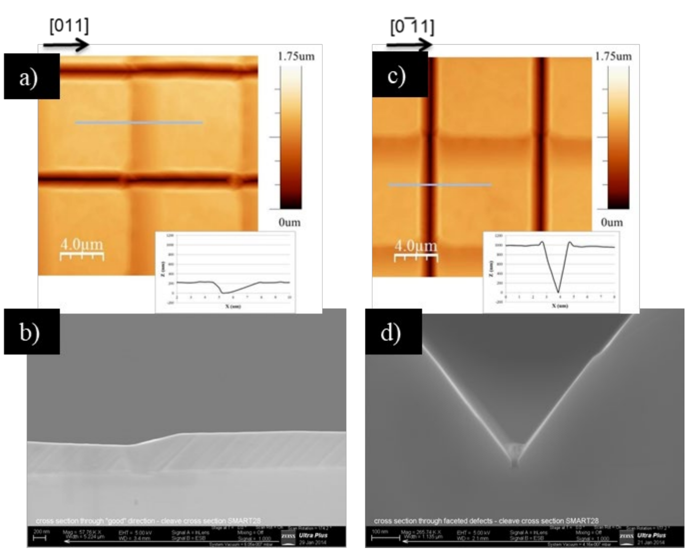

Figure 3. 20 μm x 20 μm AFM images of 1 μm GaAs MOCVD homoepitaxy with line profile (inset) and corresponding SEM cross sectional image across **a-b**) shallow 200 nm trenches in GaAs above $[0\bar{1}1]$-oriented HSQ lines. Line scan and cross section are in the [011] direction. **c-d)** AFM line scan and SEM cross sectioni across 1 μm deep facets, the full thickness of the epitaxy growth, around horizontal [011] oriented HSQ lines. Line scan and cross section are taken along $[0\bar{1}1]$. In **d)**, the ~20 nm HSQ line is visible at the bottom of the growth, with no GaAs epitaxy grown directly above.