NIRT: Extremely-Mismatched Materials for Advanced Nanodevices

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This research project is directed toward the development of high-performance nanoscale electronic devices based on extremely-mismatched materials (e.g. InAs, InSb) grown on Si substrates. The effort is inherently interdisciplinary nature, requiring concerted, collaborative effort across traditional disciplinary boundaries. Particular emphasis is placed on materials growth and characterization, surface chemistry, nanofabrication techniques, and nanoelectronic device design. Nanoscale electron devices based on extremely-mismatched materials such as InAs, InSb and the III-Sb's grown on large-area insulating substrates such as silicon-on-insulator and the associated materials growth and process technology are being explored.

A balanced program of materials and device research is being pursued. Two alternative approaches for achieving high quality material for nanoscale electronic devices based on InAs, InSb, and III-Sb heterostructures are under investigation. The first approach focuses on the growth of nanometer-scale, highly lattice mismatched layers directly on silicon and insulating substrates (e.g., Si on insulator, Ge on insulator). Our approach exploits solid phase epitaxy and recrystallization in a new context enabled by the nanoscale size of the active device material. We will carry out fundamental work to investigate the reduction of defects created during low temperature, highly lattice-mismatched heteroepitaxy in this important class of narrow bandgap materials. The second approach seeks to create and exploit new composite substrates by wafer bonding. The wafer bonded substrate is constructed from a lattice-matched epitaxial film, which is subsequently used for regrowth of epitaxial InAs, InSb, and III-Sb's for nanodevice heterostructures. An additional research topic that is critical to realizing functional nanodevices is the issue of surface passivation; non-aqueous surface passivation schemes will be investigated. These new and novel techniques for achieving highly lattice-mismatched, device quality heteroepitaxial films will not only impact an extremely important technological field, but will also provide fundamental and new knowledge in materials science.

In addition to the fundamental material questions surrounding the growth and recrystallization or wafer bonding of ultra-thin lattice mismatched layers, research into device technologies leveraging these materials is being pursued. The device research includes experimental and theoretical study of advanced nanoscale FETs for logic as well as heterostructure backward tunnel diodes for millimeter-wave and THz sensing. Two FET architectures--one based on InAs and InSb channels in an aggressively-scaled conventional FET design, and the other based on field-assisted lateral tunneling in a novel nanotransistor--are being pursued, using extremely-mismatched materials grown on scalable insulating substrates, as developed in the materials thrust. The materials and device research thrusts are tightly coupled; the needs of the device designs influence the materials development effort, and the materials effort directs the device design and enables the experimental demonstration of the proposed devices. The successful realization of these devices will have far-reaching impact on electronic systems design, as well as environmental and remote sensing.

For the epitaxial growth and recrystallization effort, a range of experiments have been performed to gain an understanding of, and control over, the nucleation of InAs on both Si and SiO_2. The removal of the oxide from the Si surface is critical to the controlled nucleation of device quality InAs. Therefore, we investigated the surface termination and cleaning of Si prior to introduction into the MBE system. In addition, the impact of substrate orientation is being explored. To date, (100), (111), and (211) surfaces have been evaluated in terms of the morphology of thin InAs films. Growth of both Si and SiO_2 was carried out over a temperature range of 220-300°C was carried out and transport measurements and structural characterization is in process. Film quality and morphology has been assessed with AFM, SEM, and XRD. Pole figure analysis of the samples clearly indicates that, under the proper growth conditions, an epitaxial relationship between the Si substrate and InAs can be obtained, and that the (001) axes in each material are tilted with respect to each other (Fig. 1a). The growth on SiO_2 under the same conditions is clearly polycrystalline (Fig. 1b).

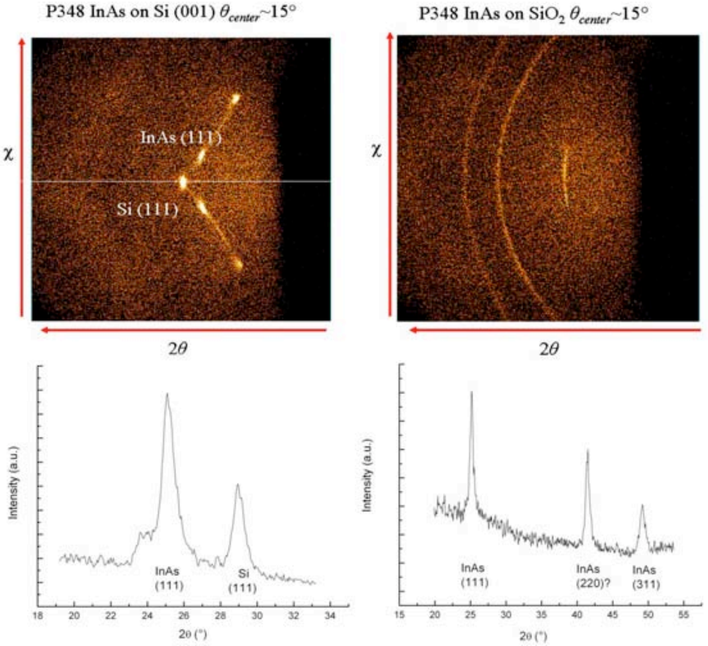
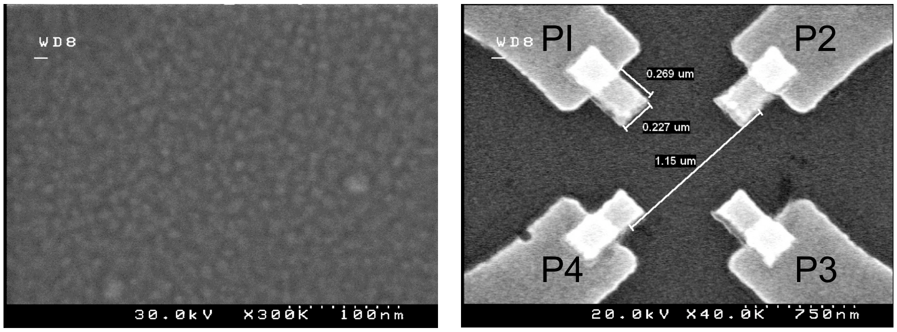


Figure 1: The pole figures and integrated intensities along the θ direction for sample InAs grown at 300 °C and annealed at 460 °C on (a) (100) Si and (b) SiO_2.

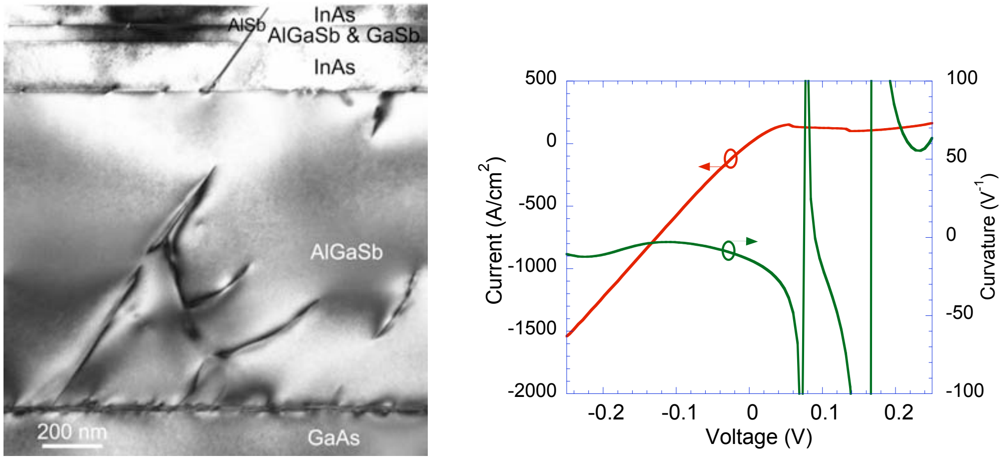
In addition to the physical characterization described previously, electrical characterization of these ultra-thin InAs epitaxial structures is on-going. The transport properties of InAs films approximately 10 nm thick are being evaluated to inform the device design effort. Scanning electron micrographs of this film show some evidence of islanding at the 10-20 nm scale, as shown in Fig. 2(a). Submicron van der Pauw test structures were fabricated on this film as shown in Fig. 2(b). Pads P1 through P4 rest on 20 nm of deposited Al_2O_3; four stitches at the ends of the pads make connections to the InAs. The transport mechanisms are under investigation for these films as a function of growth and anneal conditions. The use of nanoscale patterned substrates to nucleate growth are also being explored as a means to steer defects to electrically inactive regions of the devices.



(a) (b)

Fig. 2. Scanning electron micrographs of (a) 10 nm InAs film on (211) Si and (b) van der Pauw contacts to this same InAs film.

To explore the potential use of these materials for eventual use in electronic devices, backward tunnel diodes based on InAs/AlSb/GaSb heterostructures have also been designed and fabricated. Similar devices have been shown to be useful as millimeter-wave detectors; in this project, the emphasis is on using the performance of these devices as a means to extract the band offsets and material properties for these materials. Candidate backward diode heterostructures were grown, and first-generation devices were fabricated and characterized. Figure 3 shows typical transmission electron micrographs of a structure grown at Duke for this program. For these first-generation devices, a GaAs substrate was used in order to simplify the epitaxy; subsequent studies will focus on devices grown on Si and SiO_2 substrates with ultra-thin buffers. Good quality films were obtained, and working devices have been fabricated. Work is on-going to evaluate structures with varying Al mole fraction in the AlGaSb layer, as well as the use of Si-based substrates and thin growth buffers.



(a) (b)

Figure 3. (a) Transmission electron micrographs of backward diode heterostructure, and (b) measured I-V characteristic for a typical device.

References

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