Bismuth Surfactant-Mediated Epitaxy of Highly Doped InAs for Mid-Infrared Plasmonics

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The high carrier concentrations and mobilities achievable in InAs, which allows tuning of the plasma wavelength over a wide range of the mid- to far-infrared (IR) spectrum, coupled with the mature fabrication and processing available for III-V materials, makes InAs an interesting material for mid- and far-IR plasmonics.[1] Although many applications in the mid-IR require plasma wavelengths in the 3-5 μm range, the shortest InAs plasma wavelength reported so far is 5.6 μm.[1] Further reduction in wavelength will require higher active carrier concentrations and mobilities, as well as smooth growth morphology. However, the low growth temperatures (< 440°C) and arsenic fluxes (V/III ~ 1) typically required to grow smooth films with high dopant concentrations (> ~10^{19} cm^{-3}) can lead to amphoteric incorporation of silicon and high point-defect densities, both of which result in dopant compensation and reduced mobility.[2,3] A recent doping study in InP-based silicon-doped InGaAs suggests that dopant activation could be increased with the introduction of bismuth.[4] Here we report on the use of bismuth surfactant-mediated molecular beam epitaxy (MBE) to allow incorporation of silicon concentrations as high as ~10^{20} cm^{-3} without significant roughening, using more traditional growth temperatures (460°C) and arsenic fluxes (As_2/In BEP ~ 15), which are expected to reduce amphoteric incorporation of silicon and minimize point-defect densities, resulting in shorter plasma wavelengths.

Epitaxial films of 500 nm thick silicon-doped InAs were grown in an EPI Mod. Gen. II MBE system on sulfur-doped n-type (100) InAs substrates, with and without a bismuth overpressure (Bi BEP ~ 5×10^{-7} Torr). Characterization by optical microscopy and atomic force microscopy (AFM) showed substantial improvement in surface roughness with the introduction of a bismuth overpressure (Fig. 1), and symmetrical x-ray diffraction (XRD) ω-2θ scans of the InAs (004) diffraction peak showed a significant strain-shift due the incorporation of ~10^{20} cm^{-3} silicon atoms (Fig. 2). Reflectivity measurements of samples containing ~5×10^{19} cm^{-3} and ~10^{20} cm^{-3} silicon doping exhibited plasma wavelengths of ~5.5 μm and ~5.2 μm, respectively (Fig. 3). Attenuated total reflectance (ATR) measurements of the same samples, taken using the Otto configuration (Fig. 4), exhibited coupling to surface plasmon polariton (SPP) modes at ~6.25 μm and ~5.63 μm, respectively, demonstrating an expected shift to shorter wavelengths with increased doping (Fig. 5).

Growth on semi-insulating GaAs substrates is planned to allow direct Hall effect measurement of carrier concentrations and mobilities, and further investigation of the growth space is underway to determine the shortest achievable plasma wavelengths with and without bismuth as a surfactant.

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References

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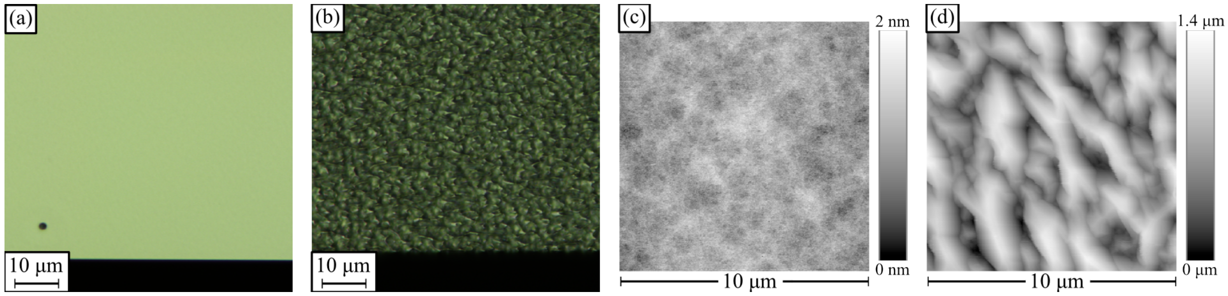

Figure 1. Optical microscopy images (100x) of the surface of 500 nm thick InAs films doped with 5×10^{19} cm^{-3} silicon atoms, grown (a) with and (b) without a bismuth overpressure. Also shown are 10 µm by 10 µm atomic force microscopy (AFM) images of the same samples, grown (c) with and (d) without bismuth. The vertical scales of the two AFM images are 2 nm and 1.4 µm, respectively.

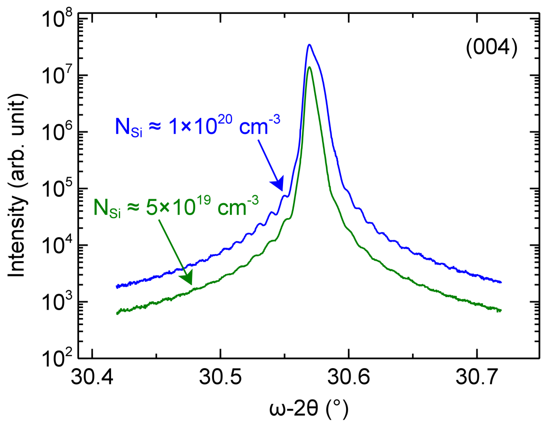

Figure 2. Symmetrical x-ray diffraction ω-2θ scans of the InAs (004) diffraction peak, showing significant strain shift due to the incorporation of silicon concentrations up to $\sim10^{20}$ cm^{-3}.

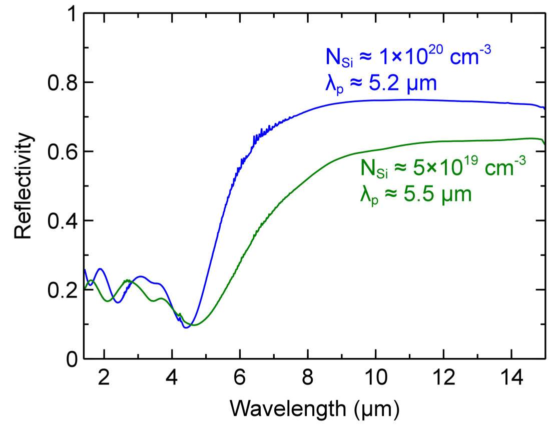

Figure 3. Reflectivity of films with $\sim5\times10^{19}$ cm^{-3} and $\sim10^{20}$ cm^{-3} silicon doping, exhibiting plasma wavelengths of ~5.5 µm and ~5.2 µm respectively.

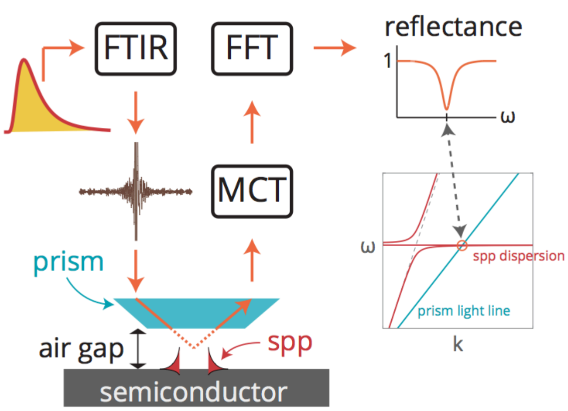

Figure 4. Schematic diagram of the Otto configuration used to measure attenuated total reflectance shown in Fig. 5. A ZnSe prism was used in the experiment.

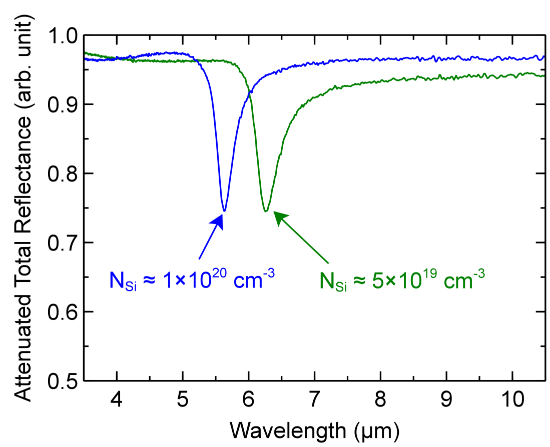

Figure 5. Attenuated total reflectance of films with $\sim5\times10^{19}$ cm^{-3} and $\sim10^{20}$ cm^{-3} silicon doping, exhibiting coupling to surface plasmon polariton modes at ~6.25 µm and ~5.63 µm, demonstrating an expected shift to shorter wavelengths with increased doping.