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Mobility Enhancement in Strained Antimonide Quantum Wells

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Background: Low-power electronics is essential for a number of military and commercial applications. Previous work at NRL has demonstrated high-performance, low-power, antimonide-based compound semiconductor transistors. In these devices, InAs is used as an electron channel with mobilities as high as 30,000 cm^2/V-s at room temperature.[1] This work has been transitioned to industry for analog applications, resulting in X-band and W-band low-noise amplifiers with record low power consumption (a factor of 3 and 10 lower than InP- and GaAs-based amplifiers, respectively). For digital and mixed-signal applications, power consumption can be minimized by designing circuits with complementary n(electron)- and p(hole)-channel transistors. These circuits consume negligible power except when being switched. Military applications for this technology are expected to include high-speed analog-to-digital conversion for high-performance radar and miniature air vehicles (MAVs), autonomous sensing, and application-specific integrated circuits (ASICs).

A major obstacle to achieving low-power complementary circuits using compound semiconductors is that hole mobilities are generally much smaller than electron mobilities. For example, the hole mobility of InAs is only 450 cm^2/V-s. The goal of our work at NRL is to produce quantum wells with hole mobility as high as possible. To do so, we have employed band-structure engineering techniques. The valence bands of semiconductors include both heavy- and light-hole bands. Under normal conditions, these bands are degenerate, meaning that both have significant hole occupation. If a strain is applied to the material, however, the degeneracy will be lifted, and the effective mass of the occupied heavy-hole band will decrease. This should lead to an increase in hole mobility because the mobility is inversely proportional to the effective mass.

Experimental Methods: For this study, we selected two heterostructures to investigate mobility enhancement by strain. To illustrate our choices, we show a plot of energy gap versus lattice constant for various semiconductors in Fig. 5. For one structure, we use the binary compound GaSb as the channel and ternary alloys of $AlAs_xSb_{1-x}$ as the barrier. We can adjust the strain in the GaSb by changing x, the mole fraction of AlAs. The other structure uses $In_yGa_{1-y}Sb$ as the channel and $Al_{0.70}Ga_{0.30}Sb$ as the barrier. In this case, the compressive strain in the quantum well increases as we increase y, the mole fraction of InSb. We grow the layers by molecular beam epitaxy (MBE) on GaAs substrates. In the MBE growth process, furnaces loaded with Ga, In, Al, As, and Sb are placed in a high-vacuum environment so that beams of atoms (or molecules) emitted from the furnace can impinge on a substrate target and form a single-crystal semiconductor film. Figure 6 is a photograph of the NRL Epicenter, which includes four MBE systems. The cross-section of our InGaSb-channel structure is shown in Fig. 7(a). A 1.5

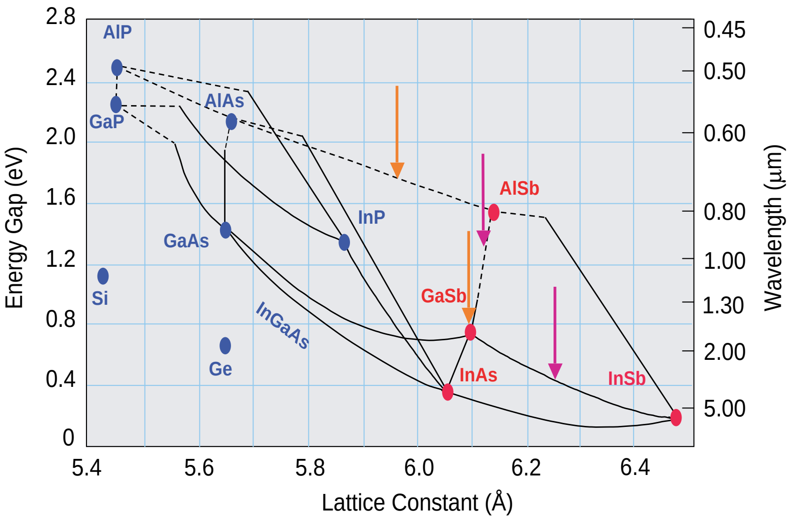

FIGURE 5
Energy gap versus lattice constant for common semiconductors. The purple arrows represent our $In_yGa_{1-y}Sb$/AlGaSb heterostructures; the orange arrows represent our GaSb/$AlAs_xSb_{1-x}$ heterostructures. In both cases, the narrow-gap quantum well is in compressive strain.

FIGURE 6
The NRL Epicenter includes four MBE systems as well as etching and analysis chambers.

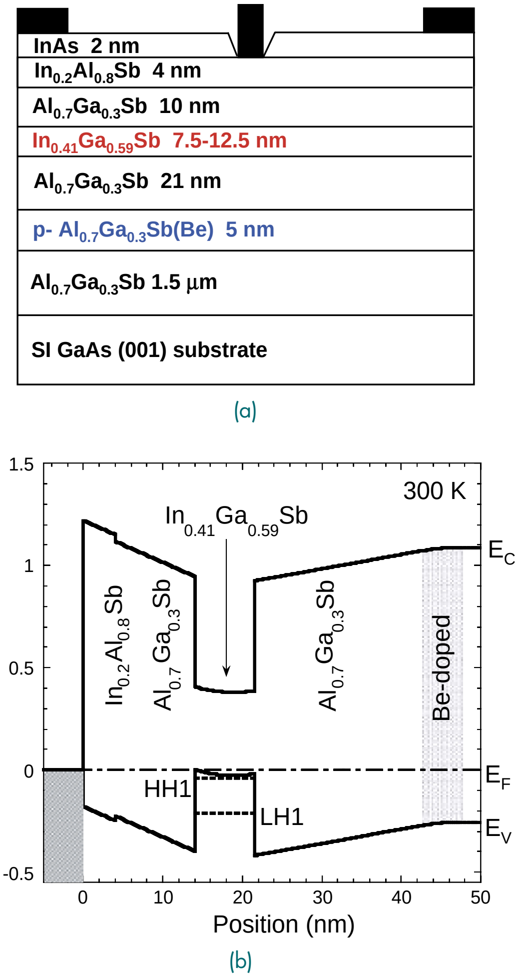

FIGURE 7
Cross section (a) and energy band diagram (b) of InGaSb-channel field-effect transistor structure.

μm thick layer of $Al_{0.70}Ga_{0.30}Sb$ accommodates the 8% lattice mismatch with respect to the GaAs substrate. The quantum well is only 7.5–12.5 nm thick. Holes are introduced in the channel by a 5-nm Be-doped layer of $Al_{0.70}Ga_{0.30}Sb$ located 21 nm below the channel. The growth is terminated by InAlSb and InAs cap layers. The band structure is shown in Fig. 7(b). The valence band offset between the AlGaSb and the InGaSb allows the confinement of holes in the InGaSb channel—an essential requirement for a p-channel transistor.

Results: The epitaxial layers were characterized by atomic force microscopy (AFM), high-resolution X-ray diffraction (XRD), and Hall/van der Pauw transport measurements. The AFM indicates the surfaces are smooth, with rms roughness values near 1–2 nm over a 5 × 5 μm area. The XRD measurements allow us to determine the composition of the ternary layers and hence the strain in the quantum wells. The transport measurements yield the mobility and density of holes in the quantum wells. Previously, three groups reported GaSb/AlGaSb quantum wells with room-temperature hole mobilities of 180–270 cm^2/V-s. For our GaSb/$AlAs_xSb_{1-x}$ heterostructures, we obtained room-temperature mobilities of 400–1100 cm^2/V-s, with the highest values for x near 0.23 and strains near 1.1%. For strains higher than 1.4%, the mobility decreased.

In Fig. 8, we plot the room-temperature mobility as a function of the InSb mole fraction for $In_yGa_{1-y}Sb$/AlGaSb heterostructures. For a quantum well thickness of 12.5 nm (pink circles), as the InSb mole fraction increases, the hole mobility increases, presumably due to enhanced strain-induced splitting of the valence bands as discussed earlier. For x values greater than 0.41, however, the mobility decreases. We also observed degradation in the structural properties measured by XRD. We attribute this to the formation of misfit dislocations in the quantum well. These dislocations form when the thickness of a mismatched layer becomes too large. We decreased the InGaSb thickness to 7.5 nm and achieved mobilities as high as 1500 cm^2/V-s, a world record for any compound semiconductor. It is clear that band-structure engineering is enhancing hole mobility.

We have fabricated transistors on both types of heterostructures and the results are promising. For example, heterojunction field effect transistors (HFETs) with gate lengths of 0.20–0.25 μm exhibit transconductances of 100–150 mS/mm and values of f_{max}, the frequency at which the transistor power gain is unity, of 27–34 GHz. Future work will focus on achieving even higher hole mobilities and integrating p-channel and n-channel transistors to demonstrate complementary circuits operating at extremely low powers.

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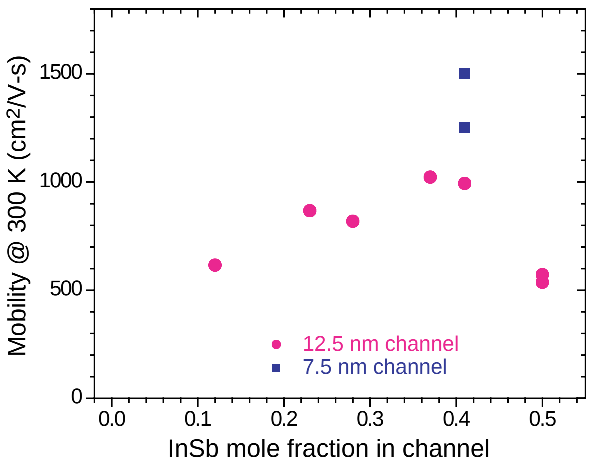

FIGURE 8
Room-temperature hole mobility as a function of InSb mole fraction for $In_yGa_{1-y}Sb$/AlGaSb quantum wells.

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