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NANOSTRUCTURES FOR ENHANCED ELECTRON/HOLE CONVERSION

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14. ABSTRACT

In this program we used molecular beam epitaxy (MBE) to create epitaxial metal-semiconductor structures containing embedded metallic nanoparticles, metallic epitaxial films and epitaxial metal-semiconductor junctions. We incorporated epitaxial metallic nanoparticles of erbium arsenide and erbium antimonide in GaAs, InGaAs and GaSb structures by molecular beam epitaxy. The metallic nanoparticles in semiconductors produced: 1) electrical doping of semiconductors, 2) electron/hole recombination enhancement, 3) electron/hole tunnel junction enhancement, 4) thermal conductivity control, 5) microwave rectification improvement and 6) strong electron plasma resonances. Tunnel currents of GaAs np junctions were enhanced by up to five orders of magnitude by the embedded nanoparticles. Electron-hole recombination times in a series of ErAs/InGaAs codepositions were reduced to less than 100 femtoseconds. We produced the first epitaxial growth of GdN on GaN. This research thus established a foundation for development of improved artificially structured thermoelectric power generation materials, for new materials for Terahertz wave generation and detection and for development of highly conducting contacts for the nitride semiconductors.

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In this program we created, studied, and developed applications for epitaxial metal-semiconductor heterostructures and nanostructures. The epitaxial metal-semiconductor nanocomposites are new electronic materials that can have substantially different properties from conventional doped semiconductors. Our approach was to use molecular beam epitaxy (MBE) growth to create epitaxial metal-semiconductor structures containing embedded nanoparticles, epitaxial films and metal-semiconductor junctions. Unlike current electronic technologies that must rely on individual dopant atoms to provide carriers and on highly imperfect polycrystalline metal films to provide electrical contacts, the new epitaxial nanoparticles and films provide a wide distribution of electron energies within a semiconductor and provide a very controlled and perfect contact to semiconductors. We studied these materials with the goal of reduction and engineering of semiconductor p-n junction barriers by embedding metallic nanoparticles in the junctions. We incorporated epitaxial metallic nanoparticles of erbium arsenide and erbium antimonide in GaAs, InGaAs and GaSb structures by molecular beam epitaxy growth. Collaborating faculty member Susanne Stemmer obtained direct evidence from Z-contrast scanning transmission electron microscopy that the metal nanoparticles of ErAs grow in a perfectly registered rocksalt structure within the zincblende semiconductor host. Current-voltage measurements showed that

1) Tunnel currents of GaAs np junctions were enhanced by up to five orders of magnitude at room temperature at one volt forward bias by incorporation of 1.2 monolayers of ErAs deposition at the junction between the n ($5\mathrm{x}10^{18}$ cm^{-3}) and p ($2\mathrm{x}10^{19}$ cm^{-3}) GaAs. The tunnel currents exceeded 10^5 Amps/cm^2 at +1 V forward bias.

2) The tunnel current enhancement was approximately one order of magnitude greater at +1 V bias for ErAs-enhanced GaAs junctions for p grown on n compared to n grown on p.
3) The tunnel current enhancement was approximately one order of magnitude greater at +1 V bias for ErAs-enhanced GaAs junctions relative to $Al_{.1}Ga_{.9}As$ junctions.
4) The tunnel current enhancement was approximately one order of magnitude greater at +1 V bias for $p = 2x10^{19}$ cm^{-3} doping of GaAs junctions compared to $p = 4x10^{18}$ cm^{-3} doping.
5) The tunnel current enhancement was approximately one order of magnitude greater at +1 V bias for 1.2 monolayers of ErAs deposition compared to 0.2 monolayers of ErAs deposition.
6) The form of the tunneling current versus voltage characteristic in the enhanced junctions was well represented by a model of tunneling in series through back to back metal- semiconductor junctions.

The first metal-semiconductor junctions (of TiPtAu on n-doped GaAs ($n = 1x10^{17}$ cm^{-3})) with and without a 0.6 monolayer deposition of ErAs two nanometers below the metal-semiconductor interface were also grown and studied. The structure with ErAs had a reduced Schottky barrier and a more ideal tunnel characteristic compared to structures with no enhancing ErAs deposition.

Carrier concentrations and electron-hole recombination rates were measured in a series of ErAs/InGaAs superlattices. Samples with 40 nm periods showed a decrease in conduction electron concentration as the deposition of ErAs increased from 0.4 to 1.6 monolayers. Samples with depositions of 1.2 and 1.6 monolayers froze out at low temperature, while samples with depositions of 0.4 and 0.8 monolayers remained fully metallic with $\sim 10^{12}$ electrons per cm^2 per layer of ErAs. Partial compensation of the carriers was achieved by modulation doping the regions near the ErAs layers with beryllium acceptors. Reduction of the superlattice period from 40 nm to 5 nm reduced electron-hole recombination times to ~2 ps (at 40 nm period) and ~0.05 ps (at 5 nm period).

In cooperation with Professor Elliott Brown, Gossard's students grew and characterized epitaxial Schottky diodes of epitaxial ErAs films on InGaAlAs of various Al contents. Reducing the Al content in the InGaAlAs reduced the Schottky barrier height continuously down to and including zero eV.

Diodes with optimum responsivity at zero applied bias were produced and measured.

We also grew fully epitaxial diodes of n-doped InAs on p-doped GaSb. Forward currents of >1000 Amps per cm^2 were measured at +1 Volt bias and were limited primarily by Ohmic contact resistance.

The metallic nanoparticles in semiconductors produced: 1) electrical doping of semiconductors, 2) electron/hole recombination enhancement, 3) electron/hole tunnel junction enhancement, 4) thermal conductivity control, 5) microwave rectification improvement and 6) strong electron plasma resonances.

ErAs particles in GaAs p-n tunnel junctions allowed much stronger tunneling than conventional p-n junctions. p-ErAs-n junctions showed up to 10^5 times more current than comparable p-n junction at 1 Volt forward bias. We synthesized cascaded photovoltaics with ErAs enhanced tunnel junctions that produced CW radiation up to 2 Thz.

We also formed epitaxial thin films of ErAs on GaAs and InGaAlAs for highly ideal and engineerable low-defect contacts and barriers for sensitive low noise mm-wave and THz detection. We measured NEP of $<9 \times 10^{-13}$ W $Hz^{-1/2}$ giving -63 dBm sensitivity at 3.1 GHz with a 8kHz bandwidth.

We developed epitaxial metal-semiconductor heterostructures and nanostructures with record-breaking performance in several areas.

1. **Cascaded solar cells with increased efficiency**. Grew cascaded AlGaAs solar cells with ErAs-enhanced tunnel junctions with output voltages of 2.1 Volts (versus 1.2 Volts with conventional tunnel junctions).

2. **ErAs nanoparticle arrays**. Produced high densities of metal nanoparticles in InGaAs by co-deposition of ErAs and semiconductor species. The arrays have high electrical conductivity, low thermal conductivity and are promising for thermoelectric power generation

3. **Highly conductive epitaxial Ohmic contacts**. Produced epitaxial ErAs epitaxial films on graded InGaAs structures. Contact resistances are less than 2 Ohm-$micron^2$.

4. **Low noise epitaxial Schottky microwave detectors**. Produced epitaxial ErAs/InAlGaAs detectors with noise equivalent power below 10^{-11} $W/Hz^{1/2}$ at 640 GHz.

5. **Terahertz detectors**. Produced ErAs nanoparticles in GaAs with best reported bandwidth and efficiency for Terahertz detectors (10 times better than radiation-damaged SOS detectors and LT-GaAs detectors).

6. **GdN on gallium nitride:** We produced the first epitaxial growth of GdN on GaN. We found growth conditions to produce micron-thick epitaxial films of GdN on GaN templates. We produced GdN (111) films with rocksalt structure on (0001) GaN at substrate temperatures below T = 500C.

The research accomplished under this grant thus established a foundation for development of highly conducting contacts for the nitride semiconductors, for development of improved artificially structured thermoelectric power generation materials, and for new materials for Terahertz wave generation and detection.

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