Enhancing photonic devices with metallic nanoparticles

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Incorporating crystalline nanoparticles in tunnel junctions dramatically reduces electrical and optical absorption losses in solar cells, as well as mid-IR and telecommunications lasers.

Tunnel junctions—traditionally highly-doped p-n junctions that operate using band-to-band tunneling—have become important building blocks of modern photonic devices. Their applications range from cascading the serially interconnecting p-n junctions in multi-junction solar cells\textsuperscript{1} to reducing electrical and optical losses in, for instance, vertical-cavity surface-emitting lasers (VCSELs).\textsuperscript{2,3} Using tunnel junctions is even being considered to circumvent the large series and contact resistances associated with p-type III-nitride materials (where III represents the group in the periodic table in which the semiconductor elements are located) for solid-state lighting.\textsuperscript{4}

Traditional tunnel junctions suffer from a number of practical difficulties related to available energy-band alignments and dopant activation, diffusion, and memory effects. These pose numerous issues with device integration and adversely affect overall semiconductor performance. Only a few ‘lucky’ materials offer the set of properties required for performance enhancement. For instance, recent advances in dilute-nitride materials have enabled generation of 1.31 and 1.55\textmu m VCSELs in gallium arsenide (GaAs)-based materials, but performance is limited by a lack of viable tunnel-junction technology.\textsuperscript{5}

Semi-metallic nanoparticle-enhanced tunnel junctions offer a universal solution to these limitations and are especially promising for GaAs-based VCSELs. Many of the rare-earth monopnictides, such as erbium arsenide (ErAs), are rocksalt semi-metals that are stable in contact with III–V semiconductors and offer compatible crystal structures for epitaxial integration as nanoparticles. Because the lattice constants of the rare-earth alloys span those of III–V and IV semiconductors, such islands could be incorporated into any semiconductor, with high quality.

GaAs tunnel junctions with semi-metallic ErAs nanoparticles embedded at the p\textsuperscript{+}/n\textsuperscript{+} interface yield \(\sim 10^5 \times\) improvement in tunneling current over traditional GaAs junctions (see Figures 1 and 2).\textsuperscript{6,7} Figures 1(a) and 1(b) show that inclusion of these nanoparticles at the tunnel-junction interface provides additional states that allow tunneling to occur in a two-step process, effectively halving the tunneling distance for each step, and dramatically increasing tunnel currents. The latter has allowed successful implementation of GaAs components into multi-junction aluminum-GaAs/GaAs solar cells.\textsuperscript{7}

However, substantial reduction in tunnel-junction ‘resistivity’ is needed for implementation into GaAs VCSELs because of their higher current-density requirements\textsuperscript{5} of \(> 10^3 A/cm^2\). Figure 3 shows that a sufficiently high-performance tunnel junction could eliminate the need for the electrically and optically lossy p-type distributed-Bragg-reflector mirror, mimicking the successful approaches used for indium phosphide-based 1.3 and 1.55\textmu m VCSELs.\textsuperscript{2,3} Therefore, we investigated the performance of ErAs nanoparticle-enhanced tunnel junctions as a function of molecular-beam-epitaxy growth parameters. By altering the nanoparticle morphology, we managed to manipulate the energy-band alignments between the metal nanoparticles and semiconductor host matrix to significantly enhance tunneling currents \(\sim 100 \times\) further (see Figure 2). These tunnel

\begin{figure}[h]
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\includegraphics[width=\textwidth]{band_diagrams.png}
\caption{Band diagrams of (a) conventional and (b) erbium arsenide (ErAs) nanoparticle-enhanced tunnel junctions, under reverse bias.\textsuperscript{6,7} \(n, p:\) Negative, positive doping. GaAs: Gallium arsenide.}
\end{figure}

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Figure 2. Current density versus voltage for conventional (black) and ErAs-enhanced tunnel junctions\(^7\) (red), and this work (green). Addition of ErAs nanoparticles enhances tunneling currents by approximately five orders of magnitude (red arrow). By controlling growth temperature and surface coverage, we further increased tunneling-current densities by \(\sim 100\times\) (green arrow).

Figure 3. By inserting a tunnel junction above the active region, the p-type distributed-Bragg-reflector (DBR) mirror can be replaced by an n-type equivalent, dramatically reducing series resistance and optical loss. Placing the tunnel junction at an optical null minimizes free-carrier optical-absorption loss.

We acknowledge A. C. Gossard of the University of California at Santa Barbara and J. M. O. Zide of the University of Delaware for many useful discussions. This work was supported by Mike Gerhold of the Army Research Office under contract W911NF-07-1-0528.

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References