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ErAs as a transparent contact at 1.55 μm

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An investigation of the optical transmission properties of semimetallic ErAs films grown by molecular beam epitaxy reveals a maximum in transmission around 1.55 μm . The semitransparent window extends from ~ 1.5 to 2.3 μm . These films were found to have resistivities less than $7 \times 10^{-5} \Omega \text{ cm}$ and permit $\sim 85\%$ transmission for a 150 nm film and $\sim 97\%$ transmission for a 15 nm film with respect to a GaAs substrate at 1.55 μm . These results suggest that ErAs may be a useful material for applications requiring transparent contacts from 1.5 to 2.3 μm . Polycrystalline films of ErAs were grown on sapphire substrates to investigate optical properties of ErAs in the visible region. © 2006 American Institute of Physics. [DOI: 10.1063/1.2354038]

Materials for transparent electrical contacts require the unusual combination of both high transparency and high conductivity. In order to achieve these two properties simultaneously, it is desirable for a material to have a moderate free carrier concentration with a high mobility to minimize free carrier absorption while maintaining a reasonably high conductivity. In addition, the energies of interband transitions should be high enough so that the interband absorption is above the region of desired transparency. The most common materials used for these applications have been doped indium oxides. The most intensively studied and utilized of these has been indium-tin-oxide (ITO).^{1,2} However, these materials are less transparent in the infrared than the visible due to free carrier absorption. As a result, higher infrared transparency is typically achieved at the expense of reduced conductivity. Several techniques have been employed to improve upon the properties of ITO. Many of these efforts have attempted to improve the electrical mobility, allowing comparable conductivities with fewer carriers. Molybdenum and titanium have both been used as alternatives to tin in order to improve the electrical mobility of indium oxide.³⁻⁵ Other research has modified the indium oxide matrix such as adding zinc⁶ or replacing the indium with cadmium, cadmium-tin-oxide (CTO).^{7,8} While these efforts have improved transparency at longer wavelengths, approaching 2 μm , they have substantially lower conductivities than those conductive oxides designed for the visible spectral range. Typically, these materials cannot be grown as single crystal films on most III-V semiconductors so that even the higher mobility materials have free carrier mobilities of less than 100 $\text{cm}^2/\text{V s}$. Semimetallic rare-earth/group-V compounds may provide another approach for achieving transparent contacts as they have lower free carrier concentrations than typical metals but larger concentrations than can be achieved in doped III-V semiconductors, comparable to those of conducting oxides. These materials have been shown to be epitaxially compatible with many III-V semiconductors, allowing the growth of single crystal films^{9,10} structurally superior to polycrystalline conducting oxides. The high quality of the single crystal

films result in higher electron mobilities than those of polycrystalline films producing higher conductivities for a given carrier concentration.

One example of a rare-earth/group-V material is ErAs, which is semimetallic and has the rocksalt crystal structure. Its lattice parameter of 5.74 Å allows ErAs to be grown epitaxially with moderate strain on both GaAs (-1.6%) and InP (2.1%) substrates. Previous research has investigated electrical and structural properties of ErAs films.^{9,11} ErAs is a semimetal with electron and hole concentrations of $\sim 3 \times 10^{20} \text{ cm}^{-3}$ and electron and hole mobilities of ~ 1000 and $\sim 500 \text{ cm}^2/\text{V s}$, respectively.^{12,13} ErAs films on InAlGaAs lattice matched to InP have been demonstrated to produce high-quality Schottky diodes with barriers that are tunable from ~ 100 to ~ 620 meV depending on the Al composition at the interface.^{14,15} In this letter we investigate the optical transmission of these ErAs films for their potential application as semitransparent epitaxial contacts to infrared devices.

ErAs films were grown by solid source molecular beam epitaxy in a Varian Gen II chamber on (100) semi-insulating GaAs substrates and on (0001) sapphire substrates. The films grown on GaAs substrates were grown on 100 nm GaAs buffer layers at a substrate temperature of 490 °C, as measured by a pyrometer. These films were singlecrystal as observed by x-ray diffraction and reflective high energy electron diffraction (RHEED). Films of 7.5, 15, 100, and 150 nm were grown on GaAs. ErAs films of 15 and 150 nm were grown on the sapphire at a thermocouple temperature of 500 °C. A more exact substrate temperature was not known because of the high transparency of sapphire at the wavelengths sampled by our pyrometer. RHEED of the surface during and after growth indicated that the ErAs films on sapphire were polycrystalline. In addition, θ - 2θ x-ray diffraction measurements, as shown in Fig. 1, indicate crystal orientations of both (111) and (001) ErAs present in the films. Examination of the films under a Nomarski microscope at a magnification of up to 500 \times indicated that the films grown on sapphire, despite being polycrystalline, were optically smooth with mirrorlike surfaces. In order to prevent oxidation, all films were capped with 10 nm of unintentionally doped GaAs.

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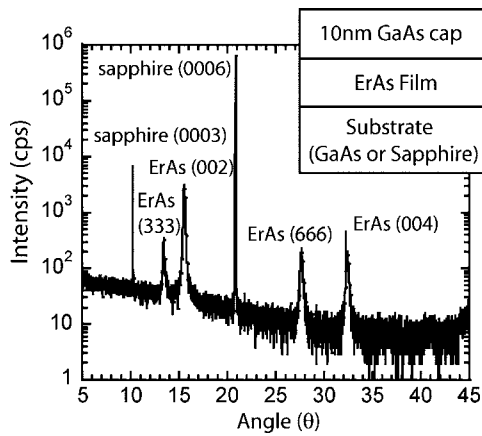


FIG. 1. θ - 2θ x-ray diffraction pattern of a 150 nm polycrystalline ErAs film on a (0001) oriented sapphire substrate. Inset shows a diagram of sample structure.

The inset in Fig. 1 shows a schematic of the sample structure. Indium was used to contact the ErAs film through the GaAs cap and a four point probe was used to measure the sheet resistance of the films. The single-crystal ErAs films on GaAs have resistivities between 6.9×10^{-5} and $10^{-4} \Omega \text{ cm}$; these values agree with those found in literature.⁹ They are also lower than typical values found in the literature for ITO and CTO films, which are typically in the low $10^{-4} \Omega \text{ cm}$.¹ The films were recharacterized several months after exposure to air. The resistivity values were very similar, suggesting that the layer of GaAs prevented oxidation of the ErAs films. The two films grown on sapphire were significantly more resistive, with measured resistivities of $1.3 \times 10^{-3} \Omega \text{ cm}$ for the 150 nm film and $5 \times 10^{-4} \Omega \text{ cm}$ for the 15 nm film. This is attributed to a decrease in carrier mobility resulting from lower structural quality of the films grown on sapphire, and increased scattering due to grain boundaries. The discrepancies in resistivities between the two samples grown on sapphire may be due to unoptimized growth of ErAs on sapphire and poor temperature control of the film during growth.

Normal incidence optical transmission and near normal incidence reflection data were obtained with a Varian CARY 500 Scan spectrophotometer. Figure 2 shows the transmission through the ErAs films of varying thicknesses on GaAs,

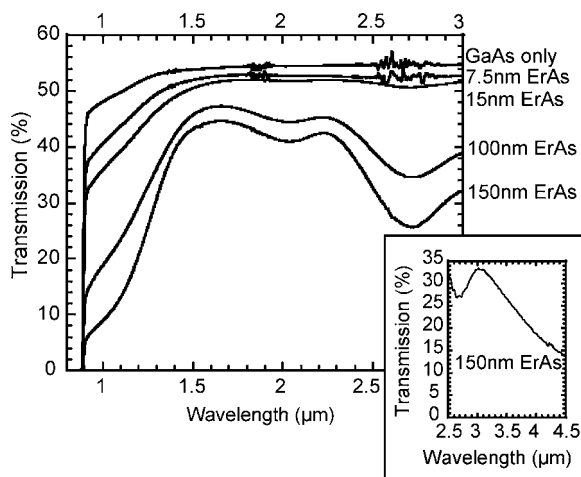


FIG. 2. Transmission vs wavelength for various thicknesses of ErAs grown on GaAs along with transmission through a GaAs substrate. Inset shows Drude tail of 150 nm layer of ErAs grown on GaAs up to 4.5 μm .

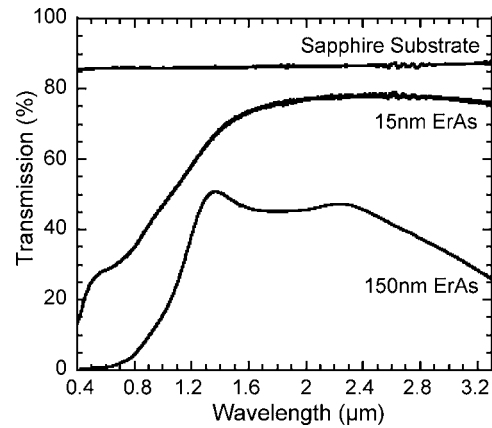


FIG. 3. Transmission vs wavelength for a sapphire substrate and for 150 and 15 nm ErAs films grown on sapphire.

in addition to a reference GaAs substrate for wavelengths from 800 to 3000 nm. As the ErAs film thickness increases, the transmission decreases. The largest decrease in transmission versus wavelength with ErAs film thickness occurs just below the GaAs band edge between ~ 980 nm and $\sim 1.2 \mu\text{m}$. To separate GaAs-substrate effects and investigate the transmission over the visible spectrum, the polycrystalline films of 150 and 15 nm grown on sapphire were measured from 400 to 3300 nm. Figure 3 shows the transmission for these two films along with that of a sapphire substrate. The sharp absorption edge at $\sim 1.1 \mu\text{m}$ is clearly visible for the films grown on sapphire suggesting that this feature is not related to the GaAs, while its dependence on ErAs film thickness suggests that it is related to a bulk property of ErAs rather than surface effects.

Band structure calculations of ErAs indicate that it is a semimetal with indirect overlapping of the conduction and valence bands.¹⁶⁻¹⁸ The valence band maximum occurs at the Γ point, while the conduction band minimum occurs at the X point. Based on the theoretical band structure computations, the gap between the valence-band Fermi level and the next higher band edge at the Γ point is between 1 and 1.5 eV.^{16,17} This agrees well with the absorption edge observed in the ErAs films around 1.1 μm (~ 1.1 eV), suggesting that this feature is a result of interband absorption around the Γ point. Additional transmission data were taken on an alternate spectrometer using a Goly cell detector to investigate the long wavelength end of the semitransparent window. The inset of Fig. 2 shows data taken with this setup up to 4.5 μm . On the long wavelength end of the semitransparent window, the decrease in transmission appears to follow a classic Drude roll-off due to the free carriers in the semimetal. However, the single crystal films grown on GaAs also exhibit an attenuation feature at $\sim 2.75 \mu\text{m}$ proportional in intensity, but not spectral position, to the ErAs thickness and not observed in the polycrystalline films grown on sapphire. The absence of spectral position dependence of this feature on film thickness suggests that it is not an interference related effect. Further investigation is required to determine the origin of this feature.

Figure 4 shows reflection and attenuation for the ErAs films grown on GaAs. The data are for light incident on the epitaxial film side of the wafer. Calculation of the exact absorption taking into account reflections and interference off of the ErAs/GaAs interfaces is nontrivial due to the un-

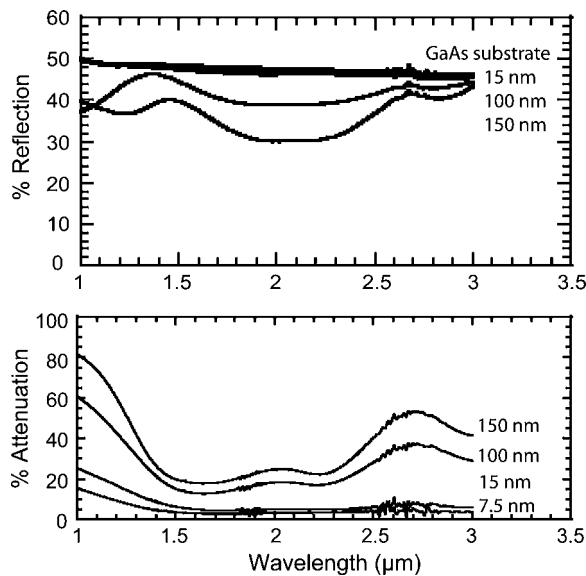


FIG. 4. Reflection, and attenuation vs wavelength for various thicknesses of ErAs films grown on GaAs. The percent attenuation is measured with respect to the transmission through a GaAs substrate.

known index of refraction of ErAs. Experimental measurement of the ErAs index of refraction is complicated by ErAs propensity to oxidize in air, requiring films to be capped with a more stable material. The index of refraction mismatch between the air and the 3.37 index of the GaAs capping layer results in about 45% loss due to reflection, as observed in the spectra for the GaAs substrate. Most of the light lost in the semitransparent region is due to reflection caused by this high index contrast between the air and the GaAs rather than absorption in the ErAs film, suggesting that transmission could further be increased with antireflection coatings. While thin films of 15 and 7.5 nm of ErAs have nearly the same reflection spectra as the GaAs substrate, the thicker films of 100 and 150 nm show some evidence of interference oscillations at the shorter wavelength end. Figure 4 shows the attenuation with respect to the transmission through a GaAs substrate. There is a semitransparent region between 1.5 and 2.3 μm . While the attenuation of the ErAs is greater than some other reported materials such as Ti doped InO for the same film thickness,⁵ the increased absorption in ErAs is compensated by a reduction in resistance due to the higher electrical mobility of carriers in the single-crystal ErAs films. A 250 nm Ti doped InO film has been shown to be greater than 85% transparent up to 1.75 μm .⁵ The resistivities of these films were measured to be $\sim 1.67 \times 10^{-4} \Omega \text{ cm}$.⁵ An ErAs film of 100 nm would have a comparable sheet resistance. The 100 nm ErAs film exhibits comparable $>85\%$ transparency with respect to the GaAs substrate from 1.5 to 1.75 μm and superior transparency of $>80\%$ up to 2.3 μm .

The fortuitous semitransparent window observed in ErAs from 1.5 to 2.3 μm wavelength combined with the ability to grow epitaxial high-quality interfaces by molecular beam epitaxy on many III-V semiconductors, may make ErAs and related rare-earth/group-V compounds useful contact materials for infrared optoelectronic devices. The semi-metallic nature of ErAs results in a higher carrier concentration than can be achieved in most semiconductors, and therefore higher conductivities, but lower carrier concentrations than most metals, which reduce the free carrier absorption at longer wavelengths. While surface oxidation of ErAs is a drawback, this may be overcome with capping materials, perhaps eventually with optically thin metals or antireflection coatings deposited *in situ*. Thus, ErAs contacts with their higher conductivity and superior interface and crystal quality may lead to substantial benefits in performance over more traditional transparent contacts for the infrared.

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