Infrared detection with a $ReSi_2$ thin film photoresistor

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Infrared detection was accomplished with the narrow bandgap semiconductor (~0.1 eV), $ReSi_2$. Photoresistors were fabricated from a polycrystalline $ReSi_2$ film grown on a silicon substrate. A light-induced decrease in resistance was observed, which was due both to film photoconductivity and to a light-sensitive contact resistance. The relative spectral response (measured at 10 K) in the wavelength range from 3000 to 6000 nm roughly follows the number of photons absorbed as estimated from the optical absorption coefficient of $ReSi_2$. Thus, the sample is a *quantum*, rather than *thermal*, detector. The mechanism of detection is believed to be the intrinsic band-to-band photogeneration of excess free carriers, leading to photoconductivity and to the reduction in contact resistance. It is suggested that $ReSi_2$ offers the potential for a new intrinsic semiconductor infrared detector technology, which may be integrated on a silicon chip, and whose absorption edge is well into the far-infrared range. © *1995 American Institute of Physics.*

Rhenium disilicide is a semiconductor possessing a bandgap near 0.1 eV.[1] Thin films of this material can be grown with excellent epitaxial alignment on Si(001), exhibiting an MeV He^+ channeling yield as low as 2%.[2] Thus, the material may lend itself to the fabrication of intrinsic semiconductor infrared detectors which could be integrated monolithically on a silicon chip and function in the long wavelength (8–14 μm) range. Furthermore, there is the possibility of bandgap engineering with $Re_xMo_{1-x}Si_2$ alloy films, which have even smaller bandgaps,[3] and which have also shown some tendency for epitaxy on Si(001) substrates.[4] An integrated rhenium silicide detector offers the potential to address the disadvantages of some infrared detector technologies in widespread current use—the lower than desired quantum yield and cutoff wavelength of platinum silicide Schottky barrier detectors, and the lack of silicon integration of HgCdTe devices.[5,6]

Yet, to our knowledge, a $ReSi_2$ photodetector has never before received serious attention by a modern research group. The basic questions include ''What would be the long wavelength limit of a $ReSi_2$-based detector? Will $ReSi_2$ provide a *quantum* detector (one whose response is due to light-induced quantum-mechanical transitions within the electronic band structure of $ReSi_2$) or a *thermal* detector (one whose response is due simply to a heating effect of the absorbed light)? What would be the actual mechanism of detection?''

To begin to explore this opportunity, we grew polycrystalline $ReSi_2$ films on silicon substrates for the purpose of demonstrating photoconductivity in the infrared range. Pure rhenium metal was deposited by E-gun evaporation. The substrates were actually thermally oxidized silicon wafers (95 nm SiO_2 formed), coated with ~500 nm of undoped (~10^6 Ω cm) polycrystalline silicon (polysilicon) after oxidation. (The purpose of the oxide was to electrically isolate the $ReSi_2$ film from the conductive silicon substrate; the purpose of the polysilicon was to provide silicon for silicide formation.) Because the substrate was held at 650 °C during rhenium deposition, formation of $ReSi_2$ by reaction of the rhenium with the polysilicon was instantaneous. Subsequently, the presence of body-centered orthorhombic[7] $ReSi_2$ was confirmed by the observation of its 011, 110, 103, and 200 peaks with conventional θ-2θ x-ray diffraction; all other diffraction peaks were attributable either to the single crystal silicon substrate or to the polysilicon layer.

We show in Fig. 1 a schematic cross section of the photoresistor sample. The electrical contacts were made by evaporating a continuous bilayer of first nickel and then gold, and then patterning the contacts photolithographically. The sample was mounted in a plug-in package and wire-bonded for the electrical measurements, which were made after placing the sample into a closed-cycle helium cryostat, whose temperature is controllable between 10 K and room temperature (as measured with a silicon diode sensor positioned on the cold finger next to the sample). At room temperature the total resistance and contact resistance values are typically 1300 and 750 Ω, respectively. At 10 K they are typically 12 000 and 7000 Ω. All photoresponse data presented in this article were obtained at 10 K.

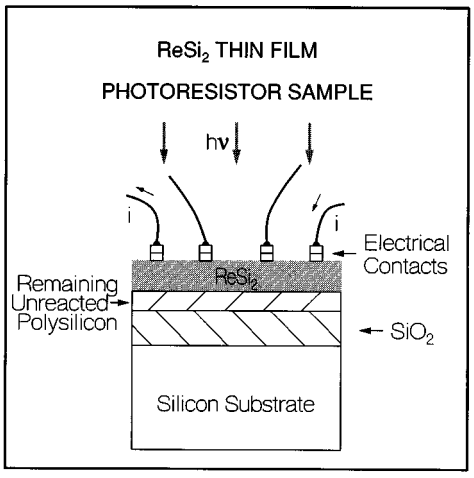

FIG. 1. Schematic cross section of the $ReSi_2$ photoresistor sample, not drawn to scale. The contacts are squares, of 0.015 cm sides. The minimum contact spacings as shown in the figure are 0.050 cm. Photoresponse data were obtained by measuring the voltage between both the outer pair of contacts (current carrying), and the inner pair of contacts (not current carrying).

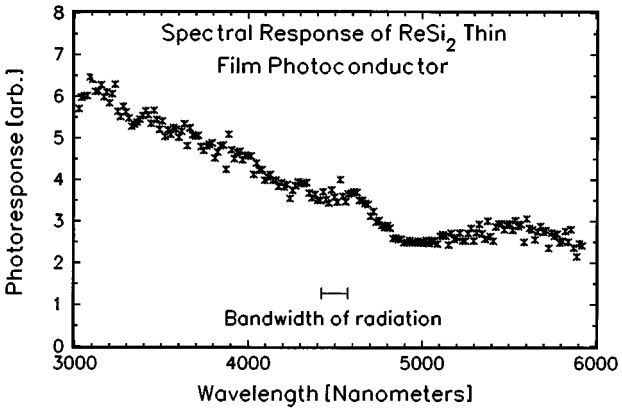

FIG. 2. Relative spectral response, normalized to photon flux, of a $ReSi_2$ photoresistor sample.

Using broadband infrared illumination, the photoresponse of the sample was measured by passing a constant current (typically 2 mA) through a pair of contacts and observing, with a lock-in amplifier, the change in potential drop (typically tens of μV) across the sample due to chopped (42 Hz) infrared radiation. The light for these experiments was in the continuous spectral range from ~2300 to 7500 nm, obtained by filtering the light from a SiC ''glowbar'' with a bandpass interference filter. The light intensity was determined with a thermopile detector. Measurements were made in both the two-point, and the four-point configurations, as suggested in Fig. 1. In the former arrangement, the voltage drop across the current-carrying contacts was measured; in the latter, the voltage drop between other pairs of contacts was measured. It was thus possible to check for light modulation of contact resistance, for a contact photovoltage, and for film photoconductivity (which means here a light-induced increase in the conductivity of the $ReSi_2$ film, whether a thermal or a quantum-mechanical effect, and whether a carrier density or mobility effect). The photoresponse increased sharply as the temperature was reduced from 50 to 10 K; it was impossible to observe a photoresponse above ~100 K.

It was found that (1) the two-point arrangement gave a larger photoresponse than any four-point arrangement (after trying numerous relative positions of the voltage-sensing contacts), (2) that there was some modulation of the contact resistance as well as the film conductivity, and (3) that for both arrangements the signal was proportional to the value of the current and to the photon flux. The film photoresponse was roughly twice the value of the contact photoresponse. We conclude that the photoresponse is a linear photoconductivity effect within the $ReSi_2$ film with additional contributions from a light-sensitive contact resistance.

The relative spectral response normalized to photon flux was obtained using the silicon carbide glowbar with a grating monochromator, together with order-sorting filters. Figure 2 shows the results for a $ReSi_2$ film of 220 nm thickness, in the wavelength range from 3 to 6 μm. There is a steady decrease in the response with increasing wavelength, by about a factor of three over the wavelength range considered. The smallest readings represent a fractional change in resistance on the order of 10^{-6}. Qualitatively similar spectral responses were obtained with both the two-point, and the four-point arrangements. While we have no explanation at present for the slight structure in the spectrum, the general decrease with increasing wavelength may be explained by considering the total absorptance of the film.

Our best estimates of the intrinsic absorption coefficient of $ReSi_2$ at 3000 and 6000 nm are $\sim 1.4\times 10^4$ cm^{-1} and 5.0×10^3 cm^{-1}, respectively.[8] Assuming constant reflectance and neglecting multiple interference effects, the absorptance may be calculated from $1-e^{-\alpha t}$, where α is the absorption coefficient and t is the film thickness. The calculated absorptance values are 0.35 and 0.13 at the two wavelengths in question. This difference is in good agreement with the relative photoresponses at those two wavelengths, suggesting that the photoresponse is proportional to the number of photons absorbed by the film. (By contrast, a comparison of the spectral response to the *power* absorbed by the film does not result in a similar agreement.)

For the purpose of demonstrating reproducibility, similar results have been obtained for other samples made from the same film as described above, and for samples made from a different $ReSi_2$ film.

The above results bear on all three questions posed. First, there is no sign of a cutoff as far out as 6000 nm (0.2 eV), the long wavelength limit of our monochromator. This is consistent with our present estimate of the bandgap of $ReSi_2$, which would cause an absolute cutoff in the vicinity of ~12 400 nm (~0.1 eV). Second, because the spectral response follows the number of photons absorbed by the film, rather than the power absorbed, it appears that $ReSi_2$ offers a *quantum*, rather than a *thermal*, detector. Regarding the third question, the fact that the photoresponse follows the calculated absorptance suggests that one actual mechanism of detection is photoconductivity due to the generation of excess carriers. (Of course, we have at present no definitive data that could distinguish photogeneration of an excess carrier density from a photoenhancement of carrier mobility.) The light sensitivity of the contact resistance may also be due to the presence of excess carriers. Further research is necessary to establish the long wavelength limit, and the details of the mechanisms of detection, of this $ReSi_2$-based infrared detector.

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