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EXTRINSIC GERMANIUM PHOTOCONDUCTORS FOR FAR-IR ASTRONOMY: RESEARCH RESULTS AND WORKS IN PROGRESS

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ABSTRACT

We report on Ge:Ga and Ge:Sb photoconductor materials and detectors that are under development by our group. Our best unstressed Ge:Ga devices exhibit dark currents lower than 200 electrons per second (e^-/s) with a concurrent responsivity of 2 A/W and detective quantum efficiency (DQE) of 5% (at T = 2 K, 1 x 10^8 photons per second illumination). For higher backgrounds an operating temperature of 3 K can be used. This increases the DQE to 7% and the responsivity to 4.5 A/W. The figures of merit are roughly the same for stressed Ge:Ga operated at 1.5 K (low background) and 2 K (high background).

Recently we began investigating n-type Ge:Sb as an alternative photoconductor material. Two crystals of Ge:Sb were grown and a number of test detectors were fabricated and evaluated. At 2 K the best device produced dark currents of less than 100 e^-/s with concurrent responsivity of 1 A/W and DQE of 4%. At 3 K the dark current increases to 10^5 e^-/s, the DQE rises to 7% and responsivity to 4 A/W.

Using p-type Ge:Ga crystals we are in the process of constructing 2-D monolithic photoconductor arrays. Our monolithic approach should afford low cost array fabrication and sensitivity similar to cavity-mounted devices. Future work will focus on measuring pixel-to-pixel homogeneity, cross talk issues, overall sensitivity, and suitability for photometric instruments.

1. GALLIUM-DOPED GERMANIUM DETECTORS

1.1 Unstressed Ge:Ga

Unstressed Gallium-doped germanium (Ge:Ga) photoconductors have been integrated into many far-IR instruments where sensitivity in the 50-120 µm wavelength band is needed [1,2]. Thirty-one of these detectors were flown on the IRAS satellite [3] and ESA's Infrared Space Observatory (ISO) is currently collecting data with 15 of these detectors [4,5].

For the past several years, our group at LBNL has been producing and testing detector materials that will satisfy the requirements in the 50-220 µm band for the Space Infrared Telescope Facility (SIRTF) proposed by NASA. This mission has placed stringent requirements on Ge:Ga photoconductor sensitivity, and we have been able to satisfy these goals. Fig. 1 shows the typical responsivity (R), DQE and Dark Current (DI) of our Ge:Ga crystal #113 material.

The shape of the DQE curve in Fig. 1 can be explained as follows. Under low bias, the detector has low responsivity, and the Johnson noise of the transimpedence amplifier (TIA) feedback resistor dominates. The DQE is therefore correspondingly low. At the high bias extreme, localized breakdown ("spiking") causes excess noise in the detector, and the DQE drops. This is a typical trend for photoconductors, and it can be seen in the ISO detectors as well our devices [4]. The best sensitivity (highest DQE) occurs with an electric field of 75-100 V/M.

The data presented in Fig. 1 are a compendium of several tests. Responsivity and DQE are measured under low background illumination using a TIA. The dark current is measured in a well-shielded "dark" dewar with an integrating amplifier [6]. All data presented were taken at an operating temperature of 2 K, since this temperature affords an acceptably low DI and high responsivity.

The #113 Ge:Ga crystal has undergone extensive evaluation, and many devices and arrays have been built to demonstrate reproducibility and uniformity of detector behavior. Reference [7] describes the most recent test results conducted on this material by the Multiband Imaging Photometer for SIRTF (MIPS) group at the University of Arizona. This work has resulted in official acceptance of crystal #113 material for use in the SIRTF flight and engineering model arrays.

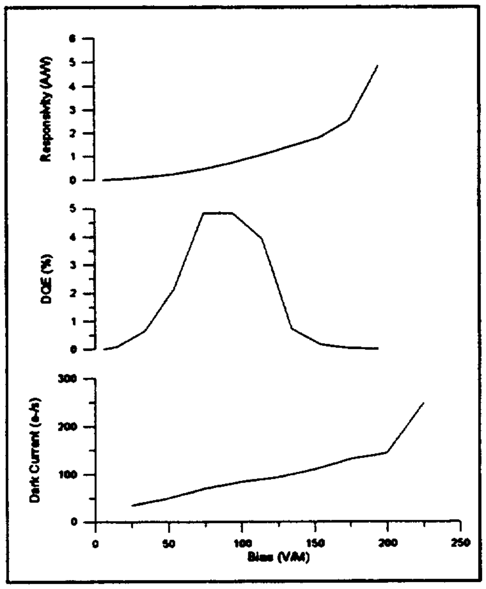

Fig. 1. Concurrent R, DQE and DI for an LBNL Ge:Ga #113 cavity detector. T = 2 K. R and DQE were determined using a chopped (23 Hz) photon source, 1.6 x 10^{-13} to 8.3 x 10^{-13} W, 89.9μm narrow-band filtered. Details in Ref. [12].

Variable-temperature Hall Effect and resistivity measurements show that the Ga acceptor concentration in this material is ≈ 2 x 10^{14} cm^{-3}, while the residual compensating donor impurity concentration is ≈ 2 x 10^{12} cm^{-3}, resulting in a compensation of 1%. Our experience indicates that when a Ge:Ga photoconductor material is more than 1% compensated, the detectors will exhibit a high DI due to variable-range hopping conduction. When a photoconductor is less compensated, carrier lifetime is increased and again DI increases. Therefore, compensation of 1% is close to the ideal case for low background space-based applications where long integration times are used. For high frequency applications such as mixers, the compensation is increased to shorten the carrier lifetime at the cost of a DI increase and responsivity decrease [8].

1.2 Stressed Ge:Ga Detectors

To obtain longer wavelength sensitivity, Ge:Ga can be mounted in a harness that applies uniaxial stress to the detector chip [9]. This technique can extend the long wavelength response edge to approximately 220 μm [10], and this approach was used to produce 8 long wavelength detectors for ISO [4,5]. At LBNL we have been fabricating and testing stressed Ge:Ga detectors for possible inclusion in SIRTF and FIRST. The test data for one of our "typical" low background devices are given in Fig. 2.

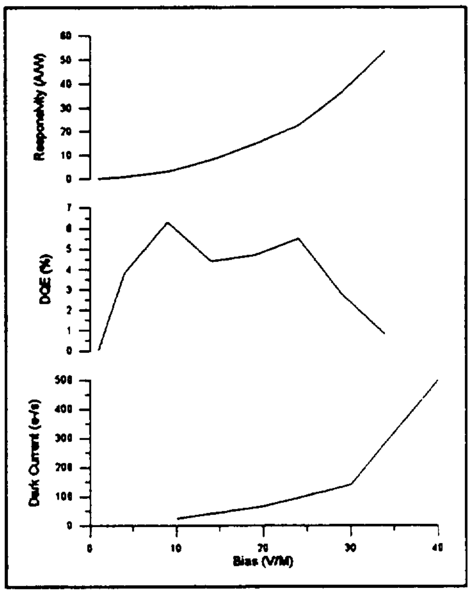

Fig. 2. R, DQE, and DI for LBNL stressed Ge:Ga 113-3.6. All data taken at 1.5 K. R and DQE were determined using a photon source chopped at 23 Hz between 4.1 x 10^{-14} and 1.5 x 10^{-13} W. A narrow band filter at λ = 163μm with bandwidth = 3.66 μm was used.

When uniaxial stress is applied to a Ge:Ga detector, the effective binding energy of the charge carriers (holes) to the acceptors is reduced. This leads to the long wavelength response mentioned earlier, but also causes an increase in the concentration of thermally excited free carriers at temperatures greater than 1.5 K. Therefore, to minimize DI, these detectors should be operated at 1.5 K or below. In addition, the stress in the lattice increases carrier mobility and lifetime [11], which accounts for some of the high responsivity and low breakdown voltage that these devices exhibit.

2. Ge:Sb PHOTOCONDUCTORS

Ge:Sb is an n-type semiconductor that responds to slightly longer wavelength radiation than unstressed Ge:Ga (≈130 μm vs. 120 μm). These 10 μm of extra bandwidth encompass the astrophysically interesting CO 21-20 spectral line (124μm) as well as the N II (121.9μm) and Si I (129.7μm) spectral lines. Until recently, however, Ge:Sb has not been thoroughly studied or optimized in terms of photoconductor performance and production.

We have grown two crystals of Ge:Sb specifically for low background photoconductor applications. The first crystal (LBNL # 830), was doped with Sb ≈ 3.5 x 10^{14} cm^{-3}. The second crystal (# 831) is more lightly doped at ≈1.8 x 10^{14} cm^{-3}. As with the Ge:Ga crystals, we controlled the primary dopant (Sb) concentration and the residual p-type impurity concentration such that the final compensation was approximately 1%. Photoconductors were prepared from each of the two new crystals, and a #113 Ge:Ga detector of identical dimension and configuration was prepared to serve as a comparison. For optical testing, each photoconductor was mounted in a polished brass cavity (the same cavity was used for all tests). For dark current testing, a completely sealed dewar was used. Ref. [12] describes this work in detail, but the important data are reproduced in Fig. 3.

The photoconductors from the new Ge:Sb crystals exhibit dark currents of less than 100 e^-/s when operated at fields that produce the best DQE for each case. The concurrent responsivity is not as high as crystal #113 Ge:Ga, but for low noise systems this will not limit sensitivity and may actually improve the dynamic range of photon fluxes detectable with these devices. We conclude from these measurements that the new Ge:Sb crystals can match the performance of the best Ge:Ga in many applications, while at the same time providing a longer-wavelength cut-on.

3. MONOLITHIC Ge:Ga ARRAYS

Large format 2-D IR detector arrays are of interest to many researchers in far-IR astronomy. The MIPS instrument team will build a large 2-D array of Ge:Ga photoconductors by constructing 1 x 32 modules and stacking these into a 32 x 32 final configuration [7,13]. The MPE/UCB FIFI instrument uses two 5 x 5 Ge:Ga arrays (one stressed, the other unstressed) fabricated from individual detector elements [14]. For future needs, however, a monolithic design like those used in CCD cameras would have distinct fabrication advantages.

Unfortunately, a monolithic approach typically compromises sensitivity in Ge-based photoconductors. Ge:Ga has a relatively high dielectric constant (≈4) which results in the reflection of 36% of a perpendicularly incident photon flux from the first surface. This loss of signal is compounded by a poor photon absorption efficiency ($\alpha \approx 2.4$ cm^{-1} for our dopant concentrations) which leads to less than ideal DQE. To compensate for these shortcomings some users have mounted each photoconductor in its own polished metal cavity. This helps reflect any unabsorbed photons back into the detector. With a 1 mm^3 detector chip this technique can boost the signal amplitude by approximately 50%. However, incorporating a cavity for each pixel of a large format array becomes quite cumbersome.

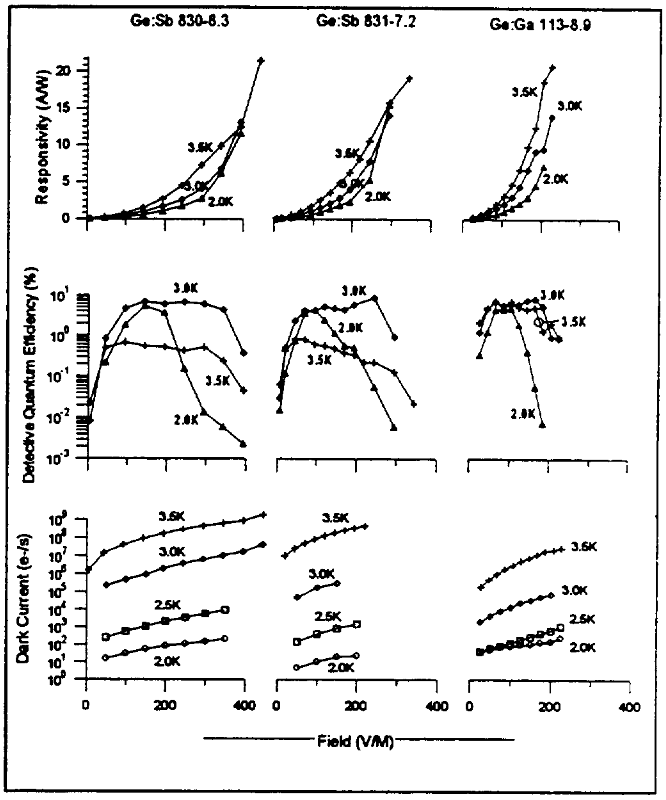

Fig. 3 A comparison between two Ge:Sb and one Ge:Ga photoconductors. R and DQE were determined using a chopped 23 Hz signal between 1.6-8.3 X 1013 W, signal centered at 89.9 μm with 11.9 μm bandwidth.

In 1994 we performed a comprehensive study to determine if Ge:Ga arrays could be built without the use of cavities and without significant loss of sensitivity [15]. As part of this effort, we constructed and tested several Ge:Ga detectors in various configurations to simulate prototype pixels that might comprise a 2-D array. The results from this study indicated that, under identical low-background conditions, a "free standing" detector can match the DQE of a cavity-mounted detector, provided that the free standing device has the appropriate configuration [15]. With the knowledge gained from the above study, we have begun to build and test 2-D arrays based on the design of our best free standing device.

Our present array concept uses a single Ge:Ga block, 2 mm thick and 8 X 8 mm in square dimension. A transparent electrode is prepared on the "front" surface by implanting a thin layer of Boron ions (B^+). The back surface is B^+ implanted and fully metallized with Pd (200Å) and Au (4000Å). Grooves are then cut into the back surface using a thin blade (150 μm) dicing saw producing an 8 x 8 grid of square Ge "pillars." The depth of the saw cuts is 1.8 mm, which leaves 0.2 mm of uncut contiguous material at the photon-incident surface of the block. The saw cuts provide nearly complete optical and electrical isolation of each pixel. To collect the electrical signals from the array, connections are made to the 8 x 8 grid of backside contacts. For this purpose, we have designed and fabricated a sapphire circuit board (fan out) that mates with the detector block and routes the signal of each pixel to individual preamps or a multiplexer. Single crystal sapphire was chosen as the fan out since the thermal contraction of this material closely matches the thermal contraction of single crystal germanium.

Fig. 4 is a photo of one of our 8 x 8 arrays that is fully assembled and ready for evaluation. Our future work on this device will include measuring the homogeneity across the array and investigating cross talk issues. If the experimental results look promising, we will investigate mounting these arrays directly to cold readouts, or designing the appropriate fan-out for array-readout interfacing.

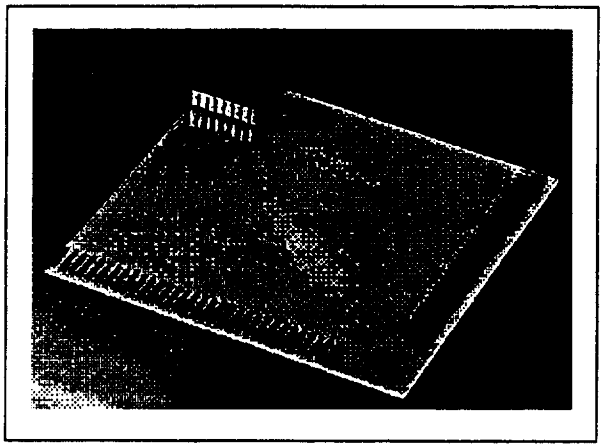

Fig. 4. A monolithic Ge:Ga Array Prototype

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