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EXTRINSIC GERMANIUM BLOCKED IMPURITY BAND DETECTORS

Timothy N. Krabach
Jet Propulsion Laboratory
Pasadena, California

James E. Huffman
Rockwell International Science Center
Anaheim, California

Dan M. Watson
University of Rochester
Rochester, New York

Ge:Ga blocked-impurity-band (BIB) detectors with long wavelength thresholds greater than 190 μm and peak quantum efficiencies of 4%, at an operating temperature of 1.8K, have been fabricated. These proof of concept devices consist of a high purity germanium blocking layer epitaxially grown on a Ga-doped Ge substrate. This demonstration of BIB behavior in germanium enables the development of far infrared detector arrays similar to the current silicon-based devices. Present efforts are focussed on improving the chemical vapor deposition process used to create the blocking layer and on the lithographic processing required to produce monolithic detector arrays in germanium. Approaches to test the impurity levels in both the blocking and active layers are considered.

For missions such as the Space Infrared Telescope Facility (SIRTF), a need exists for sensor arrays capable of background limited detection in the far infrared, from 30 to 300 μm. The state of the art for discrete FIR detectors are extrinsic germanium photoconductors, which have the combination of high responsivity and low noise required to reach the background noise limit.[1] Gallium, boron, and antimony have all been successfully used as dopants in germanium PC's, with Ge:Ga the most highly developed: it has a threshold wavelength of 120 μm, which can be extended out to 220 μm with the application of a large uniaxial stress. However, the incorporation of extrinsic germanium photoconductors into focal plane arrays presents great difficulties. The low doping densities used, ~ 10^{14} cm^{-3}, leads to long absorption lengths of about 1 cm. The large detector volume leads to two problems: it makes these detectors vulnerable to saturation and long-lasting responsivity variations from cosmic-ray particle encounters, and the long distance between electrodes would lead to large crosstalk in monolithic array formats. Finally, the necessity of mechanical stress to extend the wavelength response would greatly complicate the creation of large format arrays.

Many of these same difficulties are found in shorter wavelength silicon PC's. Recently, the development of silicon-based blocked impurity band detectors (BIBs) has resulted in large format monolithic arrays that are free of these problems, offering high quantum efficiencies and radiation hardness.[2] The success of silicon BIBs has encouraged a similar effort to be undertaken in germanium, with the goal of producing monolithic, high performance arrays working in the 30 - 250 μm range.

The advantages of the BIB concept are many.[2,3] The active region of the device is thin because the high doping concentration provides a small absorption length; in silicon BIBs the active region is roughly 20 μm thick. This gives the detector high radiation hardness: the smaller detector volume presents less of a target, and the higher number of recombination centers allows a faster recovery. Arrays benefit from less crosstalk. At low bias voltages the BIB operates much like a reverse-biased photodiode. With no recombination noise, in the background photon noise limit BIBs have a $\sqrt{2}$ sensitivity advantage over PC's. Finally, BIBs respond at longer wavelengths than corresponding extrinsic photoconductors. The origin of this is due to both the impurity banding at these concentrations,[4] and the effects of the high electric fields on the impurities (Poole-Frenkel effect).

The first working demonstration of a germanium BIB detector was made by Watson and Huffman.[5] Simple detectors were fabricated by growing an intrinsic Ge epitaxial blocking layer on a Ga-doped Ge substrate (N_A from 3-6 × 10^{16} cm^{-3}) acquired from Eagle-Picher. Spreading resistance analysis (SRA) was used to determine the thickness of the blocking layer. The wafer was cut up by a diamond saw into 2 mm^2 individual detectors. A summary of the device characteristics is provided below, along with results obtained from a high performance Ge:Ga photoconductor in a cylindrical integrating cavity. The extension of the threshold wavelength to ~ 200 μm *without* mechanical stress being applied shows the fruitfulness of developing GeBIBs. The highest bias that could be applied before breakdown was only 40 mV. It is anticipated that further development will result in higher purity blocking layers and therefore higher breakdown voltages. The one large negative found in testing these detectors was a high dark current (> 10^6 electrons/sec), which could be due to several factors. It might represent a poor blocking layer, or it might be due to leakage around the edges. Because the detector region is extremely thin, saw damage cannot be easily eliminated by etching the sides of the detector, as is done for PC's.

Table I. Summary of detector characteristics

	Ge:Ga BIB (1.7K)	Ge:Ga PC (4.2K)
Gallium density (cm^{-3})	3×10^{16}	2×10^{14}
Donor density (cm^{-3})	4×10^{12}	$< 10^{12}$
Highest bias (mV)	40	200
Threshold wavelength	192	120
Peak current responsivity (A / W)	5	39
Peak quantum efficiency	4%	16%
Photoconductive gain	1	3

The present GeBIB program at JPL is focussed on using metal halide chemical vapor deposition (CVD) for the creation of ultrapure germanium blocking layers, and later on in the program, the doped active layer as well. The requirements for a good BIB detector are: high purity ($<10^{12}$ cm^{-3} impurities), adjustable thickness of the blocking and active layers, control of majority impurity concentrations, abrupt profile between the blocking and active layers, and good crystalline quality. CVD has already proven all of these characteristics in silicon, and some in Ge. This approach also offers the possibility of testing different impurities in Ge. Gallium is the dopant being used since it has the highest absorption cross-section. Given a background donor level in the active layer, a Ge:Ga active layer will offer the highest absorption length, and thus highest Q.E. Another factor in the concentration on gallium is the availability of ultrahigh purity $GeCl_4$ as a precursor. In an effort to further extend the wavelength response of GeBIBs, another dopant that will tested as part of the program will be antimony, which possesses a cutoff wavelength of 138 μm.

Another focus of the program is the immediate development of the processing techniques needed for photolithography on ultrapure Ge wafers. One reason for the jump into this instead of working more on single detectors is the need for reproducibility in creating detectors. The large variability from detector to detector can be traced in part to the saw processing; this provides little information for trying improvements in the growth process. The second reason for this is to investigate the cause of the high dark currents observed in the original devices. Only by creating lithographically patterned detectors of different areas, and avoiding entirely the question of edge damage, can the true low-background performance of GeBIBs be found. A third reason lies in the pressing need for arrays from projects such as SIRTF. By making small linear and area arrays performance parameters such as crosstalk and uniformity can be measured. Finally, an optimized GeBIB detector, with the highest radiation hardness, will need a back-illuminated geometry such as that employed in silicon BIB arrays. This geometry requires photolithographic techniques to produce. The performance goals set out by the GeBIB program, designed to meet the needs for FIR focal planes in the SIRTF and LDR missions, are listed in Table II.

Table II. Performance Goals for GeBIB detector arrays.

threshold wavelength	250 μm
operating temperature	<2K
background conditions	$>10^5$ (SIRTF), $>10^{10}$ (LDR)
dark current	< 100 (SIRTF), < 10^5 (LDR)
quantum efficiency	> 20 %
breakdown voltage	200 mV
photoconductive gain	≥ 1
uniformity of responsivity	± 5%
crosstalk	± 2%

The major difficulty in the development of GeBIB detectors is in the inadequacy of the material testing techniques that have been used so successfully in the silicon BIB program. Beyond the standard tests for checking the crystallinity of the epitaxial layer, particularly near the interface with the doped substrate, the most important parameters to be measured are the acceptor concentration N_A in the doped layer, the residual donor concentration N_D in the doped layer, and the impurity concentration N_{BL} in the blocking layer. It is also important to identify what the impurities are in the blocking layer, to help eliminate those materials from the growth process. Of these parameters N_A is easy to determine by the resistivity of the substrate, N_D can be found after a device is fabricated, but N_{BL} cannot be measured with the presently available tools.

One measurement technique that does carry over from the silicon BIB development effort is cryogenic C-V testing, which gives the donor concentration N_D in the active region. With the sample device at its operating temperature, the device capacitance is obtained by applying a small, slow (<10 Hz), ac signal in addition to the dc bias, then measuring the amplitude and phase of the detector current. The capacitance is then derived from the complex impedance. One important point is that because of the low mobility of the A^- carriers, this testing must be done at low frequencies. The width of the depletion region can be calculated from the relation

$$C = \varepsilon\varepsilon_0 A / (d + w)$$

where C is the capacitance, A is the detector area, d is the blocking layer thickness, $\varepsilon = 15.4$ is the relative dielectric constant in germanium, and w is the depletion layer thickness. The donor concentration within the depleted layer is then found via

$$w = \sqrt{2\varepsilon\varepsilon_0 V / N_D e + d^2} - d$$

where V is the bias voltage. In the test devices the donor concentration was derived to be $N_D = 3 \times 10^{12}$ cm^{-3}. A powerful extension of this method is to measure the depletion layer thickness versus bias voltage; this differential C-V technique allows one to determine the depth profile of N_D.

The standard test to determine N_{BL} in Si BIBs is spreading resistance analysis (SRA). Due to germanium's smaller bandgap, at room temperature the intrinsic carrier concentration is ~ 2×10^{13} cm^{-3}. SRA is therefore of limited use in germanium, though it still is used to find the blocking layer thickness. However, a simple calculation reveals upon cooling the sample down to <240K, the intrinsic carrier concentration is reduced by a factor of 100. It should be possible to modify existing SRA apparatus to cool the sample and the test probes. By undertaking the SRA measurements cold, the true blocking layer impurity concentration can be found. An effort along these lines has been started.

Another possibility is the use of photothermal ionization spectroscopy (PTIS) to reveal the composition of the impurities in the blocking layer. PTIS is already used to measure the concentration of specific, shallow, hydrogenic impurities in bulk semiconductor crystals. Through the use of interdigitated electrodes implanted on the surface, the electric field would be confined to the blocking layer, and the heavily doped active region would not contribute to the photothermal signal. Though this technique could not be used on actual devices, it would provide information vital to the crystal grower to help in modifying the growth process to produce cleaner blocking layers.

The initial efforts in the GeBIB program have been in improving the epitaxial growth process and in identifying lithographic processing steps compatible with the BIB structure. A diagram of the device structure is shown in figure 1. The initial detectors produced all failed. The reasons for the devices not working were poor metal step coverage over the oxide down to the pixel, and disappearance of the boron ohmic implant. Both of these problems have now been traced back to the use of H_2O_2, utilized as a cleaning agent and a metal etch, which was found to be an excellent germanium etch as well. A new metallization scheme has been evaluated and found to produce good step coverage, and the corresponding metal etch has been verified not to harm the germanium or the boron implant. With a processing sequence now hopefully in place, both Ga and Sb-doped wafers are now being processed into detectors.

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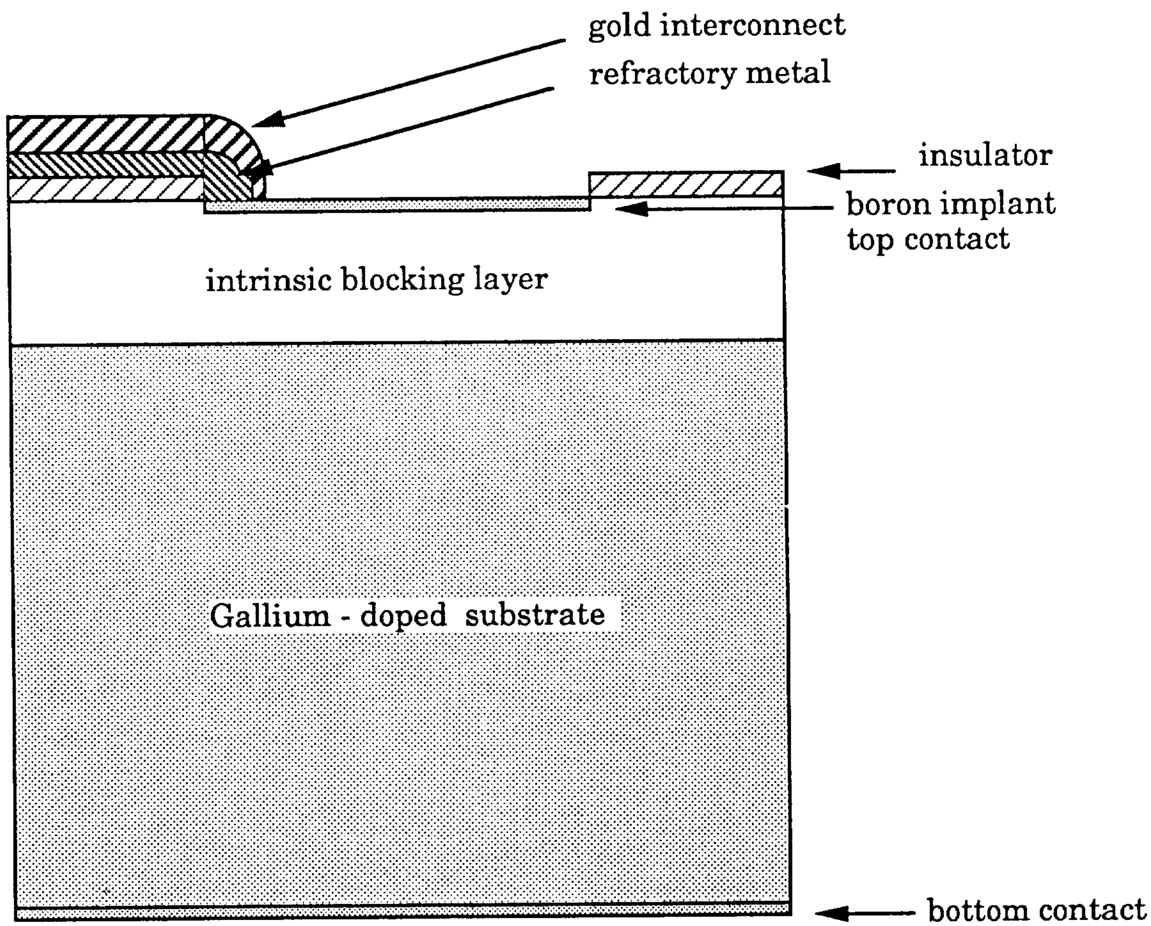

Figure 1. Outline of the first lithographically patterned GeBIB detectors. The detector is front-side illuminated, with the Ge blocking layer grown by CVD onto a commercial Ga-doped Ge substrate. Pixels range in size from 2 to 64 mils square.