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Advanced Ge Detectors for Infrared and MM Waves

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The continued interest in sensitive IR and MM wave detectors for astronomical, astrophysical, cosmological and laboratory applications has led to the development of extrinsic Ge photoconductors and Ge thermistors which can be operated near the photon noise limit for the lowest astronomical backgrounds. (1,2) Both the technology as well as the scientific understanding of operation have been advanced to the point where materials parameters and device geometries can be deliberately designed for a wide range of application. Ge detectors and detector arrays are among the most sensitive devices in the 50μm to 1mm wavelength range.

Ge photoconductors doped with the acceptors Ga and Be and with the donor Sb operate optimally between 50μm and 120μm. Mechanical uniaxial stress of Ga doped Ge (Ge:Ga) reduces the binding energy of the shallow Ga acceptors and extends the photoconductive onset to about 250μm. (3) At liquid helium temperature and below the majority acceptors (donors) are "frozen out", binding a hole (electron) which can be photoionized by the IR radiation. The lifetime of photogenerated free carriers which give rise to the photocurrent, depends on the number of ionized acceptors (donors). This number is dominated by compensating minority donors (acceptors) and not by photoionization up to very high photon fluences. One can relate the photocarrier lifetime τ to an average distance l traveled in the crystal using the mobility μ and the electric bias field E:

$$l = \mu E \tau \qquad (1)$$

The signal current I_S is obtained by

$$I_S = e\dot{N}\eta l/L \qquad (2)$$

with e = charge of the electron, $\dot{N}$ = photon flux entering the detector, η = fraction of photons entering the detector which generate a photocarrier (often called optical or responsive quantum efficiency) and L = interelectrode distance. Equation (2) represents the steady state signal current.

An often used figure of merit is the responsivity, the ratio of the signal current and the photon power:

$$R = I_S/P = e\eta l/Lh\nu \qquad (3)$$

with hν = photon energy.

The noise equivalent power (NEP) is defined as the photon power which leads to an average signal as large as the noise. In the ideal situation where only photon noise dominates we find the background limited incident photon (BLIP) NEP to be

$$NEP_{BLIP} = \sqrt{2(2\dot{N}_{total})(h\nu)^2} \qquad (4)$$

A number of processes exist which lead to additional noise, and the deviations from ideal performance is described by the square of the ratio of NEP_{BLIP} and the measured NEP. This number is commonly called detective quantum efficiency:

$$\eta_d = (NEP_{BLIP}/NEP)^2 \qquad (5)$$

Well designed systems with cooled preamplifiers reach values of ηd between 0.1 and 0.4. It has been demonstrated that these values which are significantly below unity are not affected by electronic noise but that there exists more likely a fraction of photons which do not generate free carriers after entering the detector. A further source for this excess noise may originate from the bound excited states of the shallow dopants. Free carriers can get trapped for some time before being re-emitted into the band. Such trapping processes could simulate 1/f type noise in the signal current.

Only recently Haegel et. al. have developed numerical solutions for the time dependent evolution of the photoconductor current (4,5). This problem has persisted for several decades and only oversimplified models which describe some limiting cases have been published. Haegel et. al.'s solutions show that contact effects can reach as far as a few tens of μm, distances negligible for bulk like photoconductors with dimensions of hundreds of μm. The calculations also show the often encountered complicated responses to abrupt changes in the photonfluence (e.g. "hook" response).

An interesting case also computed by Haegel et. al. is the evolution of the free carrier concentration across a photoconductor in which only the central 8% are illuminated with an increased photon flux. The mobile carriers rapidly diffuse to the edge of the illuminated section while the electric field near the contacts remains unchanged. This clearly dispels the often invoked "contact effects" in the response of photoconductors which have large reservoirs of free carriers in the contact regions (as is the case for ion implanted contacts doped to levels well above the metal-insulator transition).

Current application efforts focus on photoconductor array development. The design and construction of stressed Ge:Ga arrays for space borne applications poses special problems because of weight and long term stability and reliability problems. All these problems are in the process of being solved for the Space Infrared Telescope Facility (SIRTF) (6) and other satellite applications.

The competitors for stressed Ge:Ga photoconductors are Ge Blocked Impurity Band (BIB) detectors (7) and lightly doped GaAs photoconductors. (8) Both technologies appear to require substantial development efforts before devices of sufficient quality become available. Proof of principle exist for both types of devices but all the necessary figures of merit have not been achieved in combination.

Beyond a wavelength of 250μm Ge thermistors are the devices of choice for low background applications. The problems associated with dopant fluctuations in early semiconductors thermistors have been completely solved with the neutron transmutation doping (NTD) approach. The very large size of neutron sources used for NTD (typically nuclear reactors), the very small absorption of thermal neutrons by semiconductors a few mm thick and the perfectly random distribution of the five isotopes in natural Ge lead to perfectly randomly doped material. The numbers of Ga acceptors and As donors formed by NTD of natural Ge are:

$$[Ga] = 2.94 \times 10^{-2} cm^{-3} \text{ per } n/cm^2 s \quad (6)$$

$$[As] = 8.37 \times 10^{-3} cm^{-3} \text{ per } n/cm^2 s \quad (7)$$

The small concentration of Se double donors formed after the two beta decays of ^{77}Ge are usually neglected.

From studies of a very large number of NTD Ge crystals, we have been able to firmly establish that the resistivity ρ as a function of temperature T follows the dependence for hopping conduction derived by Shklovski and Efros (9):

$$\rho = \rho_0 \exp (\Delta/T)^{1/2} \quad (8)$$

We have shown that thermistors with resistances ranging over many orders of magnitude with operating temperatures from liquid He temperature down to 10mK can be obtained reliably with these materials.

With NTD Ge thermistors it has become possible to build uniform, efficient bolometer arrays. Several groups worldwide are developing arrays for ground based large telescopes. One very ambitious project is the Submillimetre Common User Bolometer Array (SCUBA) which is being developed by the University of Edinburgh for use on the James Clerk Maxwell telescope on Mauna Kea, Hawaii (10). Scuba will have a 91 pixel array for 438μm and a 37 pixel array for 855μm. Other efforts are underway at the 45m telescope of Nobeyama Radio Observatory in Japan (11), the 30m submillimeter telescope (IRAM) located in Granada, Spain (12) and the telescope being commissioned on Mount Graham in Arizona, USA (13).

The use of arrays with n pixels not only improves the signal gathering power by n but it also allows rejection of large scale fluctuations. In the best case a factor of n^2 improvement over a single pixel device is expected. In the case of SCUBA this would amount to a factor close to 10^4!

The availability of isotopically separated, stable Ge isotopes has opened new possibilities for controlling the ratio of the minority dopant concentration and the majority dopant concentration, i.e., the compensation. This will affect the constants ρ_0 and Δ in equation (8). Work in this area is ongoing and will be reported at this workshop by K.M. Itoh et. al.

In summary let me state that the scientific understanding and the technology of both extrinsic photoconductors and thermistors have reached very advanced levels which in turn allows the construction of uniform, efficient two-dimensional detector arrays. The simplicity of these devices is in part responsible for the excellent control and reliability of all the relevant parameters. It is this aspect which poses a challenge to future detectors which may outperform Ge photoconductors and thermistors.

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