# BIB Photoconductive Mixers

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## Abstract

Far-infrared mixers using photoconductive elements offer the promise of quantum noise limited performance at frequencies > 2 THz. The device sizes are $>2\lambda$, so no external antenna is required. Bulk photoconductive mixers, however, must have long absorption lengths because of low doping, and consequently IF bandwidths are limited to 50 MHz. A better device structure using a blocked-impurity-band (BIB) layer allows very high doping in a small device, with a consequent quantum efficiency > 25% and IF bandwidth > 1 GHz, at least in Si-devices. Progress and problems with Ge:Ga mixers for the 2-5 THz range will be discussed along with Si:Sb and Si:As devices for 8-16 THz and 11-22 THz, respectively.

## 1. Introduction

The sensitivities of heterodyne mixers have advanced to the point that quantum noise limited performance is now the goal between 0.3 and 30.0 THz. Near 0.3 - 0.5 THz, SIS mixers have already achieved double-sideband NEPs close to $4\,h\nu$ per unit bandwidth [1]. At 30 THz ($\lambda$ =10 $\mu$m), receivers using HgCdTe mixers have demonstrated quantum efficiencies of 25%, equivalent to $4\,h\nu$ performance (SSB) or $2\,h\nu$ (DSB) [2,3]. The infrared mixers are reversed biased photodiodes which are sensitive in a frequency range resonant with the bandgap of the intrinsic semiconductor. Between these frequency limits, mixer technology is less developed but rapidly improving. SIS mixers will push up to 1.2 THz, the approximate limit of NbN devices. Above this frequency HEB mixers show promise in achieving $10\ h\nu$ (DSB) performance at 3 THz and maybe even better at 6 THz, because the noise process is independent of frequency [4]. Between 6 THz and 30 THz there are no demonstrated technologies, yet there are many interesting applications in astronomy. Bulk crystals of the extrinsic semiconductors Ge and Si, doped with various elements, have good photoconductive efficiencies between 3 and 30 THz, but inadequate IF bandwidths because of slow response times. We intend to adapt a new type of photoconductive device called a blocked-impurity-band (BIB) photoconductor to solve this speed problem, and thereby realize a mixer with quantum-noise-limited sensitivity.

Photoconductors and photodiodes can be used as heterodyne mixers because their output current is proportional to the absorbed infrared power: hence a square law response to the incident electric field. For an ideal photodiode, with quantum efficiency $\eta$ and IF bandwidth $B$, the heterodyne NEP is given by [5]:

$$\mathrm{NEP} = h\nu B/\eta. \tag{1}$$

Bulk mixers using Ge doped with Ga have been investigated by a number of groups as far-infrared mixers [6-9]. But quantum efficiencies and IF bandwidths of these devices are somewhat poor because of the necessarily low doping levels and the relatively large device sizes.

Devices can be made smaller without sacrifice in quantum efficiency by increasing the doping concentration, but invariably this leads to impurity level banding and a large "dark current". A way of overcoming the impurity band conduction is to use a blocking layer of nearly intrinsic semiconductor at one contact so that impurity band conduction is blocked [10]. With a blocking layer in place, doping in the active region can be increased by a factor 100 with concomitant reduction in the device thickness. For example, Ge:Ga photoconductors, which previously needed to be 1 mm thick to get adequate absorption, can now be only 10 $\mu$m thick. Planar fabrication techniques now become applicable, so that device dimensions can be defined by photolithography and doping depths, and large arrays become practical.

## 2. Device Description

BIB devices are extrinsic photoconductors. This means a donor or acceptor impurity is introduced into the semiconductor lattice so that low lying energy levels are available for photoexcitation. For example, gallium doped into germanium produces hydrogenic energy levels at acceptor sites. Electrons can then be photoexcited into the acceptor sites from the valence band. The valence band hole and impurity band electron are collected at the electrical contacts. The spectral response for the Ge:Ga BIB lies at far-infrared wavelengths between 60-120 $\mathrm{cm}^{-1}$ [11]. One can also fabricate a BIB detector using a donor impurities such as Sb or As in a Si lattice [12]. Here the photoexcitation is an electron from a donor site into the conduction band, and the spectral response peaks near 8-15 THz (20-40 $\mu$m) for Si:Sb and 11-22 THz (13-26 $\mu$m) for Si:As. Of course to prevent thermal excitation of carriers, the devices must be cooled: below 4 K for Ge:Ga devices and below 10 K for the Si:Sb BIB. Si-based BIBs are the most highly developed, and are used in incoherent detector arrays up to

256×256 elements for far-infrared space astronomy [13]. The small detector volume is a major advantage for space applications such as the planned SIRTF Observatory. The low cosmic ray sensitivity for BIBs compared to conventional photoconductors is simply because of their much smaller volumes.

The structure of a Ge:Ga BIB is illustrated in Figure 1. Ga acceptors are doped at a level of about $3\times10^{16}$ cm$^{-3}$ into Ge, which has a donor (impurity) concentration of $4\times10^{12}$ cm$^{-3}$. The doped and blocking layers are epitaxially grown, with the active region 8 $\mu$m thick and a blocking layer with thickness $d$ = 3.5 $\mu$m. Impurities in the blocking layer are also kept as low as possible (and compensated) at about $10^{12}$ cm$^{-3}$ to maximize resistivity. The bias contact on the blocking layer is a transparent electrode that passes the infrared radiation. When a negative voltage is applied to the bias lead, electrons in the acceptor impurity band are swept away from the blocking layer over a length called the "depletion" region. The internal electric field in this region is like that in a reversed biased photodiode, and the BIB behaves in a similar manner.

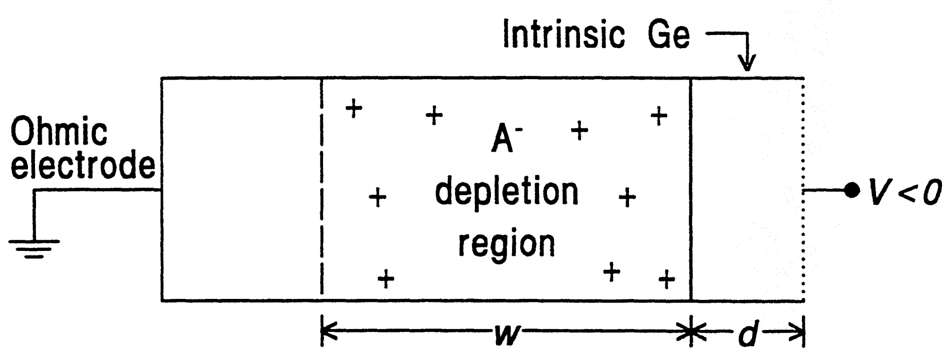


Figure 1: Schematic of a Ge:Ga BIB.

The depletion depth is a function of the applied bias, and is given by the formula [11]:

$$w = \left[(2\epsilon\epsilon_0 V/N_d e) + d^2\right]^{1/2} - d, \qquad (2)$$

where $V$ is the applied bias voltage, $\epsilon$ the relative dielectric constant (15.4 for Ge), $d$ the blocking layer thickness, and $N_d$ the density of residual donor impurities. Unfortunately, one cannot always increase the bias voltage to deplete the entire detector. The breakdown field for impact ionization of dopants and impurities limits the applied voltage to less than 60 mV for 11.5 $\mu$m thick Ge:Ga devices. Under these conditions the depletion depth is only 2.6 $\mu$m, which means most of the "active region" is undepleted. The undepleted portion has a minimal electric field given by Ohm's law, and consequently, a very very slow response (on the order of milliseconds). One could of course use a thinner device better matched to the achievable depletion depth, but this would lower the quantum efficiency. A lower number of undesired donor impurities would also help widen the depletion width for a given bias, but the impurity concentration of $4\times10^{12}$ cm$^{-3}$ for unwanted donor sites (e.g., Sb or As) in a Ge:Ga device is already very low.

Ideally, photons are only absorbed in the depletion region, because only there are the photogenerated carriers rapidly swept away to the electrical contacts. In our reverse-biased photodiode model, g=1, and the carrier lifetime is identical to the transit time, defined (approximately) as:

$$T_r = \frac{L}{\mu E}, \tag{3}$$

where $L$ is the distance between electrical contacts, $\mu$ is the carrier mobility, and $E$ is the electric field in the low field limit. The -3 dB bandwidth $B_{-3\,dB}$ for the IF response can be approximated as:

$$B_{-3\,dB} = \frac{1}{2\pi T_r} = \frac{\mu V_{max}}{2\pi L^2}. \tag{4}$$

Consequently, a wide IF requires a thin device with the highest possible bias voltage $V_{max}$. The RC limited bandwidth is generally much wider than Eq. (4) for a 50 ohm IF system. The limit on bias voltage previously mentioned restricts the maximum electric field for Ge:Ga to ~100 V/cm. For Si devices with more tightly bound sites, the field can exceed 1000 V/cm. In this latter case the carrier drift velocity reaches a terminal value near $10^6$ cm sec$^{-1}$, limited by scattering from neutral impurity sites. BIB devices such as Si:Sb and Si:As, or more exactly those with high energy dopants, have an inherent advantage over Ge:Ga BIBs for this reason. This is evident in Table 1, where the IF bandwidth is estimated for various BIBs which are 10 $\mu$m thick.

It should be noted that "compensation" is not used to improve the response time of a BIB mixer. Any increase in donor sites to effect compensation in a Ge:Ga BIB would reduce the width of the depletion region. It would also lower the current gain $g = \tau/T_r$, where $\tau$ is the carrier lifetime and $T_r$ is the transit time. Ideally, $g$ =1 for a photodiode where carriers recombine only at the contacts. Lowering the current gain increases the relative noise contribution of the IF amplifier, thereby requiring a higher LO power to achieve quantum noise limited performance. Note that a photoconductive mixer can have a power conversion gain under certain conditions [5,14].

| BIB | $V_{max}$ | $T_{min}$ | IF (-3dB)* |
|---|---|---|---|
| Ge:Ga | 60 mV | 3.3 nsec | 50 MHz |
| Si:Sb | 2.0 V | .1 nsec | 1500 MHz |
| Si:As | 2.0 V | .1 nsec | 1500 MHz |

* fully depleted material

Table 1

## 3. LO Power Requirement

Under the usual condition that $R_s \gg R_{IF}$ (where $R_s$ is the photodiode source impedance and $R_{IF}$ is the IF amplifier input impedance), the LO power required to obtain quantum limited performance (shot noise > IF amplifier noise) can be expressed as:

$$P_{LO} \geq \frac{kT_{IF}\, h\nu}{R_{IF}\, 2\eta g e^2}. \tag{5}$$

For the particular case of an IF amplifier with a 50 $\Omega$ input impedance and a noise temperature of 10 K, the required LO power is 1 $\mu$W at 3 THz. This LO power requirement can be met with a far-infrared laser even for mixer arrays. A single mixer can be driven by a laser sideband source, which can produce up to 10 $\mu$W of tunable FIR power.

Even though the BIB device has a relatively high doping density, its small volume limits the number of absorption sites. Carrier lifetimes must be short or photon fluxes small if power saturation is to be avoided. However, a minimum photocurrent is needed so that the shot noise (quantum noise) dominates over IF amplifier noise. Consequently, the response time must be fast so as to "recycle" the available impurity sites. Figure 2 shows the approximate saturation level for a Ge:Ga device as a function of carrier lifetime. The dotted line shows the LO power level at which shot noise is equal to the input noise of an IF amplifier with $T_A$ =10 K. We see that the carrier lifetime (transit time) must be significantly less than $10^{-3}$ sec to prevent hard saturation. Fully depleted devices with response times of $10^{-9}$ sec consequently do not have a power saturation problem. Undepleted devices, however, are slow and easily saturated.

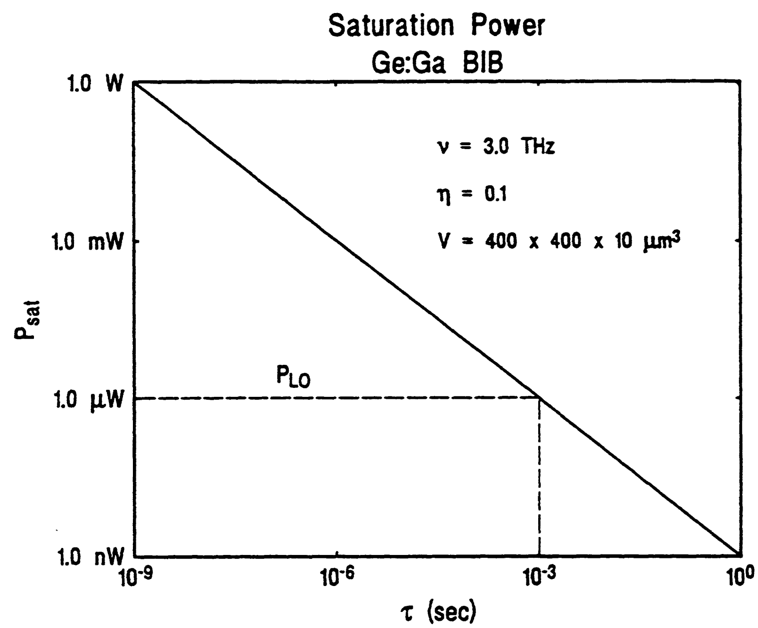


Figure 2: Saturation power for a Ge:Ga BIB as a function of carrier lifetime.

## 4. Work in Progress

Our results from tests of Ge:Ga BIBs were not promising, but that was not unexpected given the stated limitations of this material. We proceeded because Ge:Ga devices were provided to us first and because our astronomical interests lie at far-infrared wavelengths where this material is sensitive. One big problem with the devices was that they had been fabricated with a very undesirable spike on donor impurities in the active region underneath the blocking layer [15]. The depletion depth under bias conditions was minimal, and consequently the response time was slow and LO saturation was a problem. The Ge:Ga BIBs we tested were from an early attempt at epitaxial growth, and this particular impurity problem can be avoided in subsequent fabrication batches. Nevertheless, it remains to be seen whether Ge:Ga BIBs can ever prove to be competitive with HEB mixers at far-infrared wavelengths.

Si:Sb and Si:As BIBs should be competitive as mixers, not only because they work at higher THz frequencies than the established range of HEB devices, but also because they have inherent speed advantages over Ge BIBs. Of course a faster response is also needed at higher frequencies if the same Doppler velocity interval is to be observed. We hope that some good results will be available on Si:Sb and Si:As devices by the time of next year's conference. The silicon BIBs can be fully depleted and should have response times fast enough to provide usable IF bandwidths. These BIBs appear to be the only viable technology for high sensitivity heterodyne spectroscopy in the 20-40 $\mu$m region.

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