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Infrared spectral detectivity of Cr-doped GaAs

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The room-temperature spectral detectivity of Cr-doped GaAs has been examined in the impurity excitation region out to 1.7 μm, a range which includes the wavelengths of several important lasers as well as low-loss optical fibers. The results include values of $D^*$ greater than $10^{11}$ cmHz$^{1/2}$/W in the photoconductive mode, and $10^{10}$ cmHz$^{1/2}$/W in the photomagneto-optic mode. Small carrier lifetimes, ~$10^{-4}$ sec, offer the potential of high-speed operation; however, the measured response times are much larger, ~$10^{-2}$-$10^{-3}$ sec, because of very high input impedances. Formulas are presented to show the variation of $D^*$ with relevant parameters, and means of improving the performance are discussed.

PACS numbers: 85.60.Gz, 78.50.Ge, 72.40.+w

I. INTRODUCTION

In the course of some recent room-temperature dc photoconductivity measurements on semi-insulating GaAs: Cr, it was realized that many of the samples have as appreciable photoresponse at wavelengths up to 1.7 μm, well beyond the band gap of 0.87 μm. Since this response covers the intrinsic ranges of Si and Ge, several important laser wavelengths, and the low-loss region for optical fibers, it seemed worthwhile to investigate the infrared detectivity characteristics of GaAs: Cr, especially since it is already in wide use as a substrate material for GaAs FET’s and integrated circuits. In this paper, we first present formulas for the low-frequency thermal-noise-limited photoconductive (PC) and photomagneto-optic (PME) detectivities ($D^*$), in the intrinsic and extrinsic excitation regions, and then present data for $D^*$ as a function of wavelength in two representative GaAs samples. Advantages, disadvantages, and possible methods of detector-performance improvement are discussed.

II. THEORY

Perhaps the most widely used detector figure of merit is the detectivity $D^*$, given by

$$D^* = \frac{(\alpha A)^{1/2} V_x}{H A^{1/2} V_x}$$

(1)

where $V_x$ is the rms signal voltage, $V_s$ is the rms noise voltage in bandwidth $\Delta f$, and $H$ is the rms irradiance (power per unit area) falling upon a detector of area $A$. For photomagneto-optic (PME) semiconductor detectors, the dominant noise source is generally thermal, while for photoconductive (PC) detectors, thermal noise usually dominates at high frequencies, current (1/f) noise at low frequencies, and generation-recombination (g-r) noise at intermediate frequencies. The usefulness of $D^*$ as a figure of merit depends upon its independence of $\Delta f$ and $A$, which holds if $V_x/V_s \propto A^{1/2}$ and $V_s \propto (\alpha A)^{1/2}$, two conditions which are generally true but which have not been experimentally verified in this study.

The thermal noise is given by the well-known formula

$$V_{th} = \sqrt{4kT\Delta f}$$

(2)

while the g-r noise, for a nearly intrinsic semiconductor, may be obtained from

$$\frac{V_{g-r}}{V_{th}} = \frac{e}{h} \frac{V_s}{V_x} \left(\frac{\mu e A/2}{\alpha + \beta A/2} + \frac{\mu e A/2}{\alpha + \beta A/2} \right)$$

(3)

Here the symbols are as follows: $h$ is Boltzmann’s constant; $T$ is the absolute temperature; $R$ is the sample resistance; $e$ is the absolute value of electronic charge; $V_s$ is the applied voltage; $f$ is the sample length; $\mu_e$ ($\mu_h$) is the electron (hole) mobility; $\tau_e$ ($\tau_h$) is the electron (hole) lifetime; $\sigma_0$ ($\sigma_p$) is the electron (hole) conductivity; $\omega/2\pi f$ is the light modulation frequency; $\alpha$ is the fraction of neutral donors; $\beta$ is the fraction of neutral acceptors. Since the two samples of this study, A and B, both had Fermi levels near midgap, and since both contained Cr (a deep acceptor), and O (a deep donor), it is reasonable to let $\alpha$ and $\beta$, respectively, be the neutral fractions of these two impurities. For sample A, $R = 1.3 \times 10^{10}$ Ω and $f = \Delta f = 7.5$ Hz, while for sample B, $R = 2.9 \times 10^{10}$ Ω, with the same $f$ and $\Delta f$, dividing $V_x = 40$ μV rms and $V_s = 60$ μV. Furthermore, for sample B, $\tau_e = 1.4$ cm, $\mu_e = 4.0 \times 10^4$ cm$^2$/V·sec, $\mu_h = 4.0 \times 10^4$ cm$^2$/V·sec, $\tau_h = 0.55$, $\alpha = 0.48$, and $\beta = 0.55$, giving $V_{g-r}/V_{th} = 0.4$. (These parameters are taken from Refs. 3 and 4.) For sample A, $V_{g-r}$ cannot be calculated because $\tau_e$ and $\tau_h$ are unknown. The measured noise for both samples appeared to be about 100 μV rms, or less, and was independent of current at the applied voltages of this study. The frequency dependence of the noise was obscured because of the 60-Hz pickup. However, from the above considerations, it is most likely that the largest noise component was thermal and, thus, the formulas below are derived in this limit.

For a thermal-noise-limited photoconductive detector, Eq. (1) becomes

$$D_{PC}^* = \frac{\lambda E d^{1/2} \Delta \alpha}{2hc I_s (kT)^{1/2} \alpha^{1/2}}$$

(4)

where $\lambda$ is the wavelength of the light, $E$ is the electric field, $d$ is the sample thickness, $\alpha$ and $\Delta \alpha$ are the conductivity and “excess” conductivity in the light, respectively, $c$ is Planck’s constant, and $I_s$ is the light intensity (photons/m$^2$·sec). For intrinsic (above band-gap) light, the behavior of $\Delta \alpha$ is
well known, 4, 5

$$\Delta \sigma = \frac{eL_0}{d} \left[ \frac{\mu_n T \mu_p T}{d} \right] \frac{1 + \alpha \omega}{1 + \alpha L}$$

where $\alpha$ is the absorption constant, $\eta$ is the efficiency for electron-hole excitation, and $L$ is the ambipolar diffusion length, corrected for surface recombination. (The definitions of $L$ and $L_0$ may be found in Ref. 4.) Equation (5) holds under the approximations $\alpha d \ll 1$ and $d/L \gg 1$, which both are satisfied for intrinsic light, since $a > 10^3 \, cm^{-1}$, $d = 10^{-3} \, cm$, and $L = 10^4 \, cm$. From Eqs. (4) and (5), we see that $D_{PC}$, in this limit, is independent of $I_n$, $\alpha d$, and $A$, as it should be, and proportional to $E, \alpha^{1/2}$, and $d^{-1/2}$. Thus, the sample should ideally be thin and highly resistive (i.e., with low carrier concentrations, not mobilities), and should be operated in as high as possible an electric field. However, there are tradeoffs here, because above a certain value of $E$, current and g-r noise will begin to dominate thermal noise, and below a certain value of $\sigma$, the input RC time constant may limit the bandwidth, as, indeed, is the case for our samples.

For extrinsic (below band-gap) light, $\Delta \sigma$ may be written as 6

$$\Delta \sigma = eL_0 \left[ \frac{1 - \exp(-\alpha d)}{d} \right] \left[ \frac{\eta_n \mu_n T \eta_p \mu_p T}{d} \right],$$

where $\eta_n$ and $\eta_p$ are the efficiencies for electron and hole excitation, respectively. For $ad \gg 1$, $D_{PC} \ll d^{-1/2}$, while for $ad \ll 1$, $D_{PC} \approx d^{1/2}$. It can easily be shown that the maximum $D_{PC}$ occurs at $ad = 1.25$, and since $\alpha = 1 - 10^3 \, cm^{-1}$, typically, 4, 5 in GaAs :Cr, the best range of $d$ is about 0.1-1 cm. The samples used in this study were received in wafer form and were about 0.04 cm thick. Somewhat thicker samples would most likely give a higher extrinsic $D_{PC}$.

For a thermal-noise-limited PME detector, Eq. (1) may be written

$$D_{PME} = \frac{\lambda (I_{PME}/W)}{2kTe^2(n^2l^2a)^{-1/2}} ,$$

where $I_{PME}$ is the short-circuit PME current in a sample of width $w$. For intrinsic light, in the limit $ad \gg 1$, 4, 5

$$I_{PME}/W = eL_0 \eta \left( \frac{\mu_n + \mu_p}{1 + \alpha L} \right),$$

where $B$ is the magnetic field strength. Again, we desire small $d$ and $\sigma$ and large $B$ for the best $D^*$. (Present-day detector technology can probably provide $B$ = 10 kG.) Equation (8) shows, however, that in the intrinsic region $D_{PME} \ll \alpha$, in contrast to $D_{PC}$. The dependence upon $\alpha$ becomes even stronger in the extrinsic region, and, thus, since $\alpha$ falls off sharply in this region, the extrinsic PME detector is not as useful as the extrinsic PC detector, and will not be considered further in this study. (Relevant formulas for $I_{PME}$ in the extrinsic region, may be found in Ref. 4.)

It is interesting to compare the theoretical maximum $D^*$'s for GaAs, Si, and Ge. Kruse et al., 1 have compared maximum values for Si, Ge, and several other materials by making certain necessary assumptions with regard to the variable parameters, such as $E$, $B$, and $d/L$. For GaAs, we use these same assumptions as well as the following material parameters: $\mu_n = 8000$ cm²/V sec, $\tau_n = \tau_p = 10^{-6} \, sec$, $b = \mu_p/\mu_n = 20$, and an intrinsic carrier concentration $n_i = 1.7 \times 10^{16} \, cm^{-3}$. The results for GaAs are shown in Table I along with the values calculated by Kruse et al., 1 for Si and Ge. These data suggest that GaAs might be a competitive detector material, even in the 1.0-1.5- $\mu$ region, if the $D^*$'s at 0.7 $\mu$ could be extended to these longer wavelengths without too much degradation. It is the objective of this study to determine this possibility. The reason that Si has a higher theoretical PC detectivity than GaAs is its much longer lifetime (1 msec, assumed), this is a disadvantage, of course, with regard to maximum frequency response.

### III. EXPERIMENT

The two samples chosen for this study are representative of a large group of GaAs :Cr crystals which have already been investigated by various techniques. Sample A, of dimensions 9 x 5 x 0.4 mm, was one of the most "$n$ type" of this group, with a room-temperature dark resistivity of $3.5 \times 10^3 \, \Omega \cdot cm$ and a Fermi level 0.645 eV from the conduction band. On the other hand, sample B, of dimensions 14 x 6 x 0.4 mm, was one of the more "$p$ type", with a room-temperature resistivity of $1.2 \times 10^{10} \, \Omega \cdot cm$ and a Fermi level of 0.699 eV. Further data on these samples may be obtained from Refs. 3 and 4.

The sample resistances were measured with a Keithley 610C electrometer, operated in the "fast-feedback" mode. In this mode, feedback is applied through the sample, reducing the effective input capacitance, in our case, from about 20 to about 0.5 pF. This is quite important for the response speed of these samples, which have resistances $> 10^{10} \, \Omega$, but even so the time constants were still relatively large, about 5 msec for sample A and 25 msec for sample B. The unity-gain output of the electrometer was applied to a PAR 124 lock-in amplifier, operated in the ac voltmeter mode, and the output of the lock-in amplifier was read, in turn, on a Systron-Donner 7205 digital multimeter. The bandwidths of the electrometer and digital multimeter were about 40 and 200 kHz, respectively, while the bandwidth of the lock-in amplifier was set at 7.5 Hz, somewhat less than the input bandwidth of sample B. The chopping frequency was also set at 7.5 Hz, since this was the minimum frequency of our chopper. Appreciably higher frequencies diminished the signal for sample B.

In order to give convenient signal-to-noise ratios

<table>
<thead>
<tr>
<th>Material</th>
<th>Mode</th>
<th>Assumed peak wavelength ($\mu$)</th>
<th>$D^*$ (cm Hz^{1/2}/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAs</td>
<td>PC</td>
<td>0.7</td>
<td>$3.98 \times 10^{11}$</td>
</tr>
<tr>
<td></td>
<td>PME</td>
<td>0.7</td>
<td>$2.49 \times 10^{11}$</td>
</tr>
<tr>
<td>Si</td>
<td>PC</td>
<td>1.0</td>
<td>$1.71 \times 10^{15}$</td>
</tr>
<tr>
<td></td>
<td>PME</td>
<td>1.0</td>
<td>$1.74 \times 10^{11}$</td>
</tr>
<tr>
<td>Ge</td>
<td>PC</td>
<td>1.5</td>
<td>$7.21 \times 10^{13}$</td>
</tr>
<tr>
<td></td>
<td>PME</td>
<td>1.5</td>
<td>$1.23 \times 10^{10}$</td>
</tr>
</tbody>
</table>

*From Ref. 1.

TABLE I. A comparison of room-temperature theoretical maximum $D^*$s for Si, Ge, and GaAs.
The measured room-temperature spectral detectivities of GaAs:Cr samples A and B, operated in photovoltaic (PV) and photomagneto- electrostrictive (PME) modes. The chopping frequency and bandwidth are both 7.5 Hz. Also shown is a GaAs Ref. 1.

FIG. 1. The measured room-temperature spectral detectivities of the noise was ambiguous, because of pick-up. However, the rms noise, read at the digital multimeter, was approximately 100 μV. This value, about a factor of 2 higher than the calculated thermal noise voltages, was used in the calculations of $D^*$. It would be interesting and beneficial to measure the frequency, bandwidth, and temperature dependences of the noise more precisely, but such measurements were beyond the scope of this study.

IV. RESULTS

The results are presented in Fig. 1. For sample A, $D_{PC}^{*} > 4 \times 10^{10}$ cm Hz$^{1/2}$/W from 0.7 to 1.6 μm, a range which covers several important laser wavelengths (e.g., GaAs, In$_{0.5}$Ga$_{0.5}$As, and Nd$^{3+}$: YAG) as well as the low-loss region for optical fibers. A glance at Fig. 10.11 of Ref. 1, a compilation of room-temperature $D^*$'s for several detector materials, shows that the $D^*$'s measured in our study are quite competitive. (The GaAs PV-detector data, shown in Fig. 1, are also taken from Fig. 10.11 of Ref. 1.) The $D_{PME}^{*}$ data for sample B are somewhat lower than the corresponding $D_{PC}^{*}$ data, and furthermore fall off rapidly in the extrinsic region, due to the strong dependence of $I_{ph}$ upon $\alpha$. However, a PME-mode detector does have the advantage of unbiased operation. These are the highest PME $D^*$'s measured in any material, to our knowledge.

A disadvantage of our GaAs:Cr as a detector material is the slow response time (about 5 msec), due to the high circuit input impedance. This response time could be improved by either reducing the capacitance of the input circuitry or by decreasing the resistance of the crystals themselves. The former could perhaps be accomplished by an integrated-circuit approach. One easy way to help accomplish the latter would be to increase the thickness from about 0.4 to 4 mm; this would not only decrease $\tau$ by an order of magnitude, but would probably also, as shown earlier, increase $D_{PC}^{*}$. Such improvements are worth considering because the very short carrier lifetimes (10$^{-4}$ sec) offer great potential for high-speed operation if the aforementioned problem can be solved.

In summary, it appears that GaAs:Cr could well be a useful detector material for wavelengths as large as 1.6 μm. Its advantages include: (1) a relatively high $D^*$; (2) potentially high-speed operation; (3) easy availability. Furthermore, other necessary elements of the detector circuitry could be epitaxially grown right onto the GaAs:Cr detector crystal used as a substrate. The main problem precluding high-speed operation, at present, is the small input bandwidth due to the high resistivity of the material. This problem could perhaps be solved by one of the approaches outlined above.

8The values of $\mu_1$, $\mu_2$, and $\nu_1$ are the commonly accepted lattice-limited mobilities at room temperature; see, for example, articles by D. L. Rode, and by J. D. Wiley, in Semiconductors and Semimetals, edited by R. K. Willardson and A. C. Beer (Academic, New York, 1975), Vol. 11. The values of $r_1$ and $r_2$ are typical of those often measured for GaAs samples, including the samples described in this report. The value for $n_1$ has recently been measured in this laboratory and has been published; see Ref. 3.