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Infrared spectral detectivity of Cr-doped GaAs^{a)}

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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 μ , 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 photomagnetoelectric mode. Small carrier lifetimes, $\sim 10^{-8}$ sec, offer the potential of high-speed operation; however, the measured response times are much larger, $\sim 10^{-3}$ – 10^{-2} 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.

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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 μ , well beyond the band gap of 0.87 μ . 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 photomagnetoelectric (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 by¹

$$D^* = \frac{(\Delta f)^{1/2}}{HA^{1/2}} \frac{V_s}{V_N}, \quad (1)$$

where V_s is the rms signal voltage, V_N is the rms noise voltage in bandwidth Δf , and H is the rms irradiance (power per unit area) falling upon a detector of area A . For photomagnetoelectric (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 Δf and A , which holds if $V_s/V_N \propto A^{1/2}$ and $V_N \propto (\Delta f)^{1/2}$, 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

$$V_{th} = (4kTR\Delta f)^{1/2}, \quad (2)$$

while the g-r noise, for a nearly intrinsic semiconductor, may be obtained from²

$$\left(\frac{V_{g-r}}{V_{th}}\right)^2 = \frac{e}{kT} \frac{V_a^2}{l^2} \left(\frac{\alpha \mu_n \tau_n \sigma_n / (\sigma_n + \sigma_p)}{1 + \omega^2 \tau_n^2} + \frac{\beta \mu_p \tau_p \sigma_p / (\sigma_n + \sigma_p)}{1 + \omega^2 \tau_p^2} \right). \quad (3)$$

Here the symbols are as follows: k is Boltzmann's constant; T is the absolute temperature; R is the sample resistance; e is the absolute value of electronic charge; V_a is the applied voltage; l is the sample length; μ_n (μ_p) is the electron (hole) mobility; τ_n (τ_p) is the electron (hole) lifetime; σ_n (σ_p) is the electron (hole) conductivity; $\omega/2\pi \equiv f$ is the light modulation frequency; α is the fraction of neutral donors; β 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 α and β , respectively, be the neutral fractions of these two impurities. For sample A, $R \approx 1.3 \times 10^{10} \Omega$ and $f = \Delta f = 7.5$ Hz, while for sample B, $R \approx 2.9 \times 10^{10} \Omega$, with the same f and Δf , giving $V_{th}^A \approx 40 \mu V$ rms and $V_{th}^B \approx 60 \mu V$. Furthermore, for sample B, $\tau_n \approx \tau_p \approx 6 \times 10^{-9}$ sec, $V_a = 29$ V, $l = 1.4$ cm, $\mu_n \approx 4.6 \times 10^3$ cm²/V sec, $\mu_p \approx 4.0 \times 10^2$ cm²/V sec (estimate), $\sigma_n/(\sigma_n + \sigma_p) \approx 0.65$, $\alpha \approx 0.48$, and $\beta \approx 0.55$, giving $(V_{g-r}/V_{th})_B \approx 0.4$. (These parameters are taken from Refs. 3 and 4.) For sample A, V_{g-r} cannot be calculated because τ_n and τ_p 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

$$D_{PC}^* = \frac{\lambda E d^{1/2} \Delta \sigma}{2hcI_o (kT)^{1/2} \sigma^{1/2}}, \quad (4)$$

where λ is the wavelength of the light, E is the electric field, d is the sample thickness, σ and $\Delta \sigma$ are the conductivity and "excess" conductivity in the light, respectively, h is Planck's constant, c is the speed of light, and I_o is the light intensity (photons/m² sec). For intrinsic (above band-gap) light, the behavior of $\Delta \sigma$ is

^{a)}Work performed at the Avionics Laboratory, Wright-Patterson Air Force Base, under Contract No. F33615-76-C-1207.

well known,^{4,5}

$$\Delta\sigma = \frac{eI_0\eta(\mu_n\tau_n + \mu_p\tau_p)}{d} \frac{1 + \alpha L_0}{1 + \alpha L} \quad (5)$$

where α is the absorption constant, η 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 $\alpha d \gg 1$ and $d/L \gg 1$, which both are satisfied for *intrinsic* light, since $\alpha > 10^4 \text{ cm}^{-1}$, $d \approx 10^{-1} \text{ cm}$, and $L \approx 10^{-4} \text{ cm}$. From Eqs. (4) and (5), we see that D_{PC}^* , in this limit, is independent of I_0 , Δf , and A , as it should be, and proportional to E , $\sigma^{-1/2}$, 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 σ , 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 as⁴

$$\Delta\sigma = eI_0 d^{-1} [1 - \exp(-\alpha d)] (\eta_n \mu_n \tau_n + \eta_p \mu_p \tau_p), \quad (6)$$

where η_n and η_p are the efficiencies for electron and hole excitation, respectively. For $\alpha d \gg 1$, $D_{PC}^* \propto d^{-1/2}$, while for $\alpha d \ll 1$, $D_{PC}^* \propto d^{1/2}$. It can easily be shown that the maximum D_{PC}^* occurs at $\alpha d \approx 1.25$, and since $\alpha \approx 1-10 \text{ cm}^{-1}$, typically,^{4,6} 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

$$D_{PME}^* = \frac{\lambda(I_{PME}/w)}{2hcI_0(kT)^{1/2}\sigma^{1/2}d^{1/2}}, \quad (7)$$

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

$$I_{PME}/w = eI_0 B \eta (\mu_n + \mu_p) \alpha L L_0 / (1 + \alpha L), \quad (8)$$

where B is the magnetic field strength. Again, we desire small d and σ and large B for the best D^* . (Present-day detector technology can probably provide $B \approx 10 \text{ kG}$.) Equation (8) shows, however, that in the intrinsic region $D_{PME}^* \propto \alpha$, in contrast to D_{PC}^* . The dependence upon α becomes even stronger in the extrinsic region, and, thus, since α 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 parameters⁸: $\mu_n = 8000$

TABLE I. A comparison of room-temperature theoretical maximum D^* 's for Si, Ge, and GaAs.

Material	Mode	Assumed peak wavelength (μ)	D^* (cm Hz ^{1/2} /W)
GaAs	PC	0.7	3.98×10^{13}
	PME	0.7	2.49×10^{12}
Si ^a	PC	1.0	1.71×10^{15}
	PME	1.0	1.74×10^{11}
Ge ^a	PC	1.5	7.21×10^{13}
	PME	1.5	1.23×10^{10}

^aFrom Ref. 1.

cm²/V sec, $\tau_n = \tau_p = 10^{-8} \text{ sec}$, $b \equiv \mu_n/\mu_p = 20$, and an intrinsic carrier concentration $n_i = 1.7 \times 10^8 \text{ cm}^{-3}$. 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- μ region, if the D^* 's at 0.7 μ 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 $9 \times 5 \times 0.4 \text{ mm}$, was one of the most "n type" of this group, with a room-temperature dark resistivity of $3.5 \times 10^8 \Omega \text{ cm}$ and a Fermi level 0.645 eV from the conduction band. On the other hand, sample B, of dimensions $14 \times 6 \times 0.4 \text{ mm}$, was one of the more "p type", with a room-temperature resistivity of $1.2 \times 10^9 \Omega \text{ cm}$ 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

FIG. 1. The measured room-temperature spectral detectivities of GaAs:Cr samples A and B, operated in photoconductive (PC) and photomagnetolectric (PME) modes. The chopping frequency and bandwidth are both 7.5 Hz. Also shown is a GaAs sample operated in the photovoltaic (PV) mode at 90 Hz, from Ref. 1.

(about 10–50), the irradiance levels were varied from 0.1 to 100 pW/cm² with the aid of neutral-density filters. At such small light intensities, the dark characteristics of the samples were essentially unchanged.

As mentioned earlier, the detailed frequency dependence of the noise was ambiguous, because of 60-Hz pick-up. However, the rms noise, read at the digital multimeter, was approximately 100 μ V. 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, $D_{PC}^* \geq 4 \times 10^{10}$ cm Hz^{1/2}/W from 0.7 to 1.6 μ , a range which covers several important laser wavelengths (e.g., GaAs, In_xGa_{1-x}As, and Nd³⁺:YAG) as well as the low-loss region for optical fibers.⁹ 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_{PME} upon α . 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 τ 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 (10⁻⁸ 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 μ . 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.

¹P.W. Kruse, L.D. McGlauchlin, and R.B. McQuistan, *Elements of Infrared Technology* (Wiley, New York, 1962).

²A.G. Milnes, *Deep Impurities in Semiconductors* (Wiley, New York, 1973), p. 283.

³D.C. Look, *J. Appl. Phys.* **48**, 5141 (1977). Samples A and B are designated F₄ and E₂, respectively, in this reference.

⁴D.C. Look, *Phys. Rev. B* **16**, 5460 (1977).

⁵F. Adduci, A. Cingolani, M. Ferrara, and A. Minafra, *J. Appl. Phys.* **45**, 5000 (1974).

⁶A.L. Lin and R.H. Bube, *J. Appl. Phys.* **47**, 1859 (1975).

⁷P.W. Kruse, in *Semiconductors and Semimetals*, edited by R.K. Willardson and A.C. Beer (Academic, New York, 1970), Vol. 5, Chap. 2.

⁸The values of μ_n and μ_p 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 τ_n and τ_p are typical of those often measured for GaAs samples, including the samples described in this report. The value for n_i has recently been measured in this laboratory and has been published; see Ref. 3.

⁹A.G. Chynoweth, *Phys. Today* **29**, 28 (1976).