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EVIDENCE FOR SUPERRADIANCE IN THE RECOMBINATION RADIATION FROM CdTe

Lynette B. Van Atta and Gerald S. Picus
Hughes Research Laboratories
Malibu, California 90265
Amnon Yariv
California Institute of Technology
Pasadena, California 91109

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Linewidth narrowing attributed to superradiance has been observed in near bandgap radiation due to the recombination of impact ionized carriers in *n*-type CdTe at room temperature. The light emission was associated with a current breakdown that occurred at a threshold field of 12,000 V/cm in highly compensated *n*-type samples.

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The recombination radiation studies were made on a number of samples from one boule in which the resistivity ranged from .06 to 8 Ω-cm. The room temperature electron mobilities observed in this material ranged from a low of 40 to a high of 750 cm^2/V-sec. These low values, together with the observation that the mobility decreased as the temperature was decreased, led us to conclude that ionized impurity scattering is dominant in all of these samples, even at room temperature. The samples were approximately 0.6×0.8 mm^2 in cross section and 0.3 mm long in the direction of current flow. They were cleaved from single crystal sections of the original boule and indium-silver solder contacts were applied. The samples are driven with 25 nsec wide pulses from a stripline source with a 2 Ω impedance.

The *I-V* characteristics of the samples (Fig. 1) showed a current breakdown at 12,000 V/cm accompanied by a marked increase in the recombination radiation emitted. When viewed with an infrared image converter, the emission appears to be uniform over the entire sample. Occasionally, dark striations parallel to the direction of the current flow are observed in the uniform field but narrow filaments[2] have never been seen. The emission spectrum peaks at approximately 8900 Å (1.40 eV), just below the room temperature bandgap at 1.43 eV, and so is attributed to electron-hole recombination which probably proceeds through the shallow impurity centers present in the highly compensated materials. The peak intensity and halfwidth of the emitted radiation show marked dependence on the current in the breakdown region. Normalized spectra of the recombination radiation at three different levels of pump current are shown in Fig. 2. In Fig. 3, the peak intensity, I_p, the halfwidth, ΔE, and the product of peak intensity and halfwidth, $I_p\Delta E$, for this particular sample are plotted as a function of pump current. These results are representative of the data taken on a number of samples studied. In all cases, the line narrowed with increasing pump current and until its width was reduced by a factor of almost 3. At higher drive currents the emission line once again

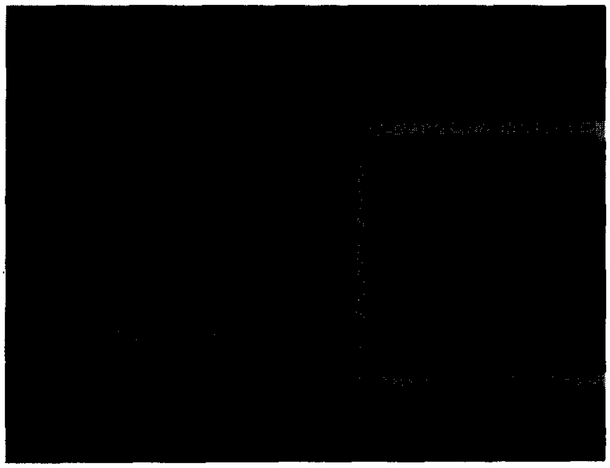

Fig. 1. Current-voltage characteristic for samples of *n*-type CdTe heavily doped with indium. The insert is a continuous display of the interval outlined on the full current-voltage relation. The voltage scale is 50 V/div and 100 V/div for the insert and the full characteristic, respectively. Both current scales are 11.5 A/div.

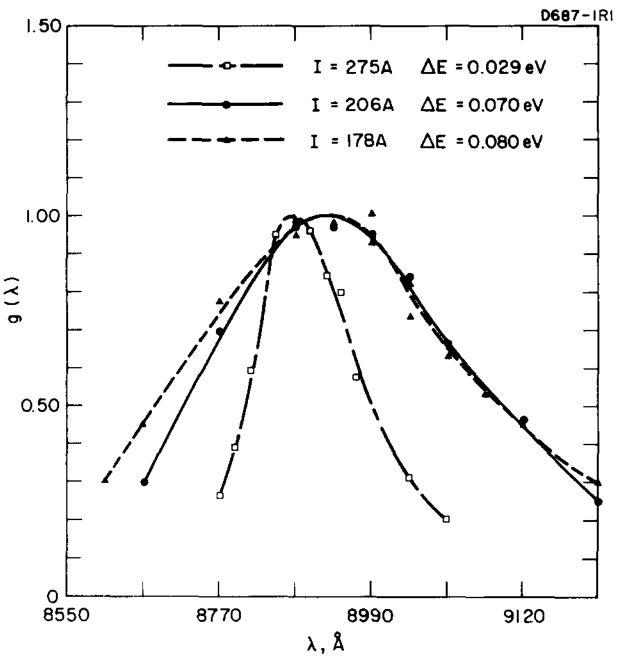

Fig. 2. Normalized spectra of recombination from *n*-type CdTe at three different pump currents. The spectrometer was able to resolve a 17 Å wavelength interval.

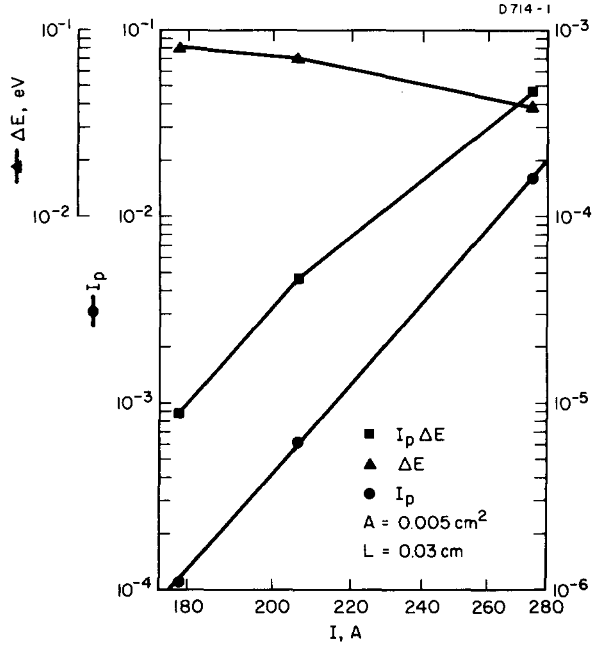

Fig. 3. Peak intensity I_p, halfwidth ΔE, and the product of peak intensity and halfwidth $I_p\Delta E$, are plotted as a function of pump current. Note that both vertical and horizontal scales are logarithmic.

broadened and matched very closely the line shape observed at low pump levels. Both I_p and $I_p\Delta E$ increase superlinearly with current.

Two effects were considered as an explanation of the observed narrowing. One is superradiance and the other is the cooling of a hot carrier distribution due to interaction with optical phonons predicted by Paranjape and D'Alba.[3] Calculations based on this latter mechanism yielded narrowing effects no greater than 10% as compared to the observed value of almost a factor of 3. Furthermore, ionized impurity scattering, which we presume is dominant in these samples, would quench the effect.[4]

If the observed line narrowing is assumed to be due to superradiance then the ratio of the halfwidths of the superradiant emission to the halfwidth of the spontaneous emission is given by[5]

$$\frac{\delta\nu}{\Delta\nu} \cong \frac{1}{ag(\nu_0)L}; \tag{1}$$

$\delta\nu$ is the observed superradiant linewidth, $\Delta\nu$ is the spontaneous emission linewidth, $g(\nu)$ is the normalized spontaneous line shape function, ν_0 the frequency of peak intensity and L is the length of the sample in the direction of observation. The quantity a is given by

$$a = \frac{(c/n)^2N}{8\pi\nu^2\tau_{\rm rad}}; \tag{2}$$

N is the inverted carrier population density, n is the indes of refraction of the medium and $\tau_{\rm rad}$ is the radiative recombination time. With the substitution, $VN/\tau_{\rm rad} = I\eta/e$ (I is the current, η the quantum efficiency, V the sample volume), we can write an expression for the quantum efficiency in terms of experimentally observable quantities.

$$\eta = \frac{(\Delta\nu)^3}{(\delta\nu)^2L}\,\frac{8\pi\nu^2\,eV}{(c/n)^2I}. \tag{3}$$

For the sample whose properties are illustrated in Figs. 2 and 3, η is found to be 5.6. Values between 5 and 10 were observed in all samples where the effect was found.

A quantum efficiency greater than 1 is not surprising if (1) the recombination lifetime, τ, due to all possible processes is less than the transit time, T, of a carrier across the sample, and (2) the probability, η' of photon emission during a recombination is high, $\eta' = \tau/\tau_{\rm rad} \approx 1$. The quantum efficiency, η, calculated in the preceding paragraph is the product of the mean number, m, of recombination events a carrier undergoes in traversing the sample and the probability η'. Since $m = T/\tau$, $\eta = m\eta' = T/\tau_{\rm rad}$, and with the substitution $T = L/\mu E$ (L is the length of the sample, μ the electron mobility, and E the electric field intensity) we can calculate the radiative recombination time: $\tau_{\rm rad} = L/\mu E\eta = 2.3 \times 10^{-9}$ sec. We have assumed that the low field mobility determined from the ohmic portion of the I-V curve is applicable in the breakdown region. An estimate of the radiative lifetime using the theory of van Roosbroeck and Shockley[6] and assuming a step function dependence of the absorption coefficient on photon energy, with bandgap and effective mass parameters characteristic of CdTe, gives order of magnitude agreement with this value of τ_{rad}.

Since on the average an electron experiences a potential drop of $V_0 = EL/m = 63$ V in one mean drift distance, the overall power efficiency of our sample can be estimated assuming $\eta' = 1$ as $P = (h\nu_0/e)/(EL/m) \cong 1\%$. The pumping mechanism producing the electron-hole density necessary for superradiance is presumed to be impact ionization. Granger[7] has estimated the threshold fields for impact ionization in polar semiconductors for the case where optical phonon scattering is dominant. For recombination times of 10^{-9} sec his estimates give breakdown thresholds of the order of 6000 V/cm if the mean time required for a hot carrier to produce an electron-hole pair is 10^{-12} sec. The threshold for impact ionization increases as this time increases and also if other scattering mechanisms, such as ionized impurities, are present. The threshold field of 12,000 V/cm which we observed is therefore consistent with these estimates. Double injection is not a reasonable alternative pump mechanism because, in the 25 nsec pulse width, holes could not drift across the entire sample even if they had mobilities close to the observed maximum of 100 cm^2/V-sec in CdTe.

The broadening of the line observed at very high pumping levels is not understood at this time, but probably results from an increased heating of the electrons at these higher fields. There still remains a question why hot carriers in these compensated samples give up their energy predominantly in an impact ionization process rather than by transfer to a subsidiary minimum with a consequent saturation of the current and initiation of the Gunn effect. A possible explanation for this is given in the accompanying Letter,[1] where it is pointed out that the magnitude of the negative differential mobility is decreased in the presence of ionized impurity scattering.

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[1] G. S. Picus, D. F. DuBois, and L. B. Van Atta, *Appl. Phys. Letters*, p. 81, this issue.

[2] M. R. Oliver, A. L. McWhorter, and A. G. Foyt, *Appl. Phys. Letters* **11**, 111 (1967).

[3] V. V. Paranjape and E. D'Alba, *Proc. Phys. Soc.* **85**, 945 (1965).

[4] D'Alba and Ward, Mexican Physical Society Meeting, Mexico City (1962), unpublished.

[5] Amnon Yariv, *Quantum Electronics* (John Wiley and Sons, Inc., 1967), p. 280.

[6] W. van Roosbroeck and and W. Shockley, *Phys. Rev.* **94**, 1558 (1954).

[7] R. Granger, *Phys. Stat. Sol.* **16**, 599 (1966).

IMPROVED PERFORMANCE OF PULSED NOBLE GAS ION LASERS WITH AN AXIAL MAGNETIC FIELD

Milton Birnbaum
Aerospace Corporation
El Segundo, California

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The output of pulsed argon ion lasers with an axial magnetic field was studied as a function of magnetic field, current, inside diameter, pressure, and oscillating wavelength. The increased output and efficiency obtained by use of an axial magnetic field clearly indicate its advantages. A simple method of providing the required magnetic field is described.

An axial magnetic field is always used in CW noble gas ion lasers because of the increased output power available at the same tube current.[1,2] In the case of pulsed ion lasers, axial magnetic fields are rarely used, because the cost of providing the required axial magnetic field outweights the modest increased power output that can be gained.[3] A simple method has been tested that provides the required magnetic fields so economically that the balance is clearly shifted in favor of operation with an axial magnetic field. In this method, the high currents in the laser discharge tube (50 to 300 A) are fed through a coil (typically several hundred turns) wound directly over the laser discharge tube, result-