a Lorentzian, we may write

$$\Delta j/j_0 \propto G_{aa}{}^{I}\exp[2\xi(\omega)x_a]$$

$$\propto (1+\bar{\epsilon}^2)^{-1}\exp(-\alpha\bar{\epsilon}), \quad (11a)$$

$$\bar{\epsilon} = (\omega-\epsilon_r)/\Gamma, \quad (11b)$$

$$\alpha = x_a\,\xi(\epsilon_r)\Gamma/|\epsilon_r|, \quad (11c)$$

where the resonance is at $\epsilon_r < 0$, and Γ is the width of the resonance.

Equations (11) are valid for $|\omega-\epsilon_r|/|\epsilon_r| \ll 1$. For values of Γ, x_a, and ϵ_r equal to 1, 2.5, and -5 eV, respectively, $\alpha = 0.6$. A plot of (11a) is shown in Fig. 2 for $\alpha = 0$, 0.6, and 0.9. For $\alpha = 0.6$ and 0.9, the peak is shifted by 0.33Γ and 0.62Γ below the actual position of the adsorbate resonance and the curves are not Lorentzian in shape; thus $G_{aa}{}^{I}(\omega)$ must be "unfolded" from the experimental curves.

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Identification of Auger Electrons in GaAs

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Auger electrons resulting from across-the-gap recombination are believed to have been identified by their velocity distribution which does not depend on the energy of the exciting photons.

One of the mechanisms responsible for nonradiative recombination of electron-hole pairs in semiconductors is sometimes believed to be Auger recombination. In the Auger process to be considered, the energy released by the recombination of an electron-hole pair is transferred to a second electron which can dissipate this energy by multiphonon emission within the conduction band.

The occurrence of the Auger effect in across-the-gap recombination in semiconductors has been surmised on theoretical grounds; but, at best, its manifestation has been indirect: the emission of photons having an energy higher than expected from thermodynamic consideration.[1,2] The much shorter carrier lifetime than calculated from detailed balance,[3] the temperature-dependent reduction of carrier lifetime,[4,5] and the carrier concentration dependence of radiative efficiency[6] are other indirect plausible consequences of Auger recombination.

In this Letter we report the direct observation of the hot electrons believed to be generated by Auger interaction. The hot electrons are emitted into vacuum where their kinetic energy distribution is measured. From the characteristic distribution of emitted electrons and its dependence on the excitation energy, it is possible to differentiate between Auger electrons and other hot electrons. In other words, it is possible to identify that component of the emission current which is due to Auger excitation.

Wafers of p-type GaAs doped to have a net hole concentration of 8×10^{16} cm^{-3} and 2×10^{17} cm^{-3} were used; n-type material was avoided to permit reducing the electron affinity by surface treatment. Heavily doped p-type material was also avoided for two reasons: (1) to increase the nonequilibrium electron concentration (the lifetime decreases with increasing doping), and (2) to reduce the competing process in which an Auger interaction between one electron and two holes results in the generation of a hot hole. The GaAs was polished and etched and then mounted in the vacuum chamber illustrated in Fig. 1 where it could be cesiated. The photoluminescence spectrum of the specimen used reveals transitions attributed to band-to-band as well as

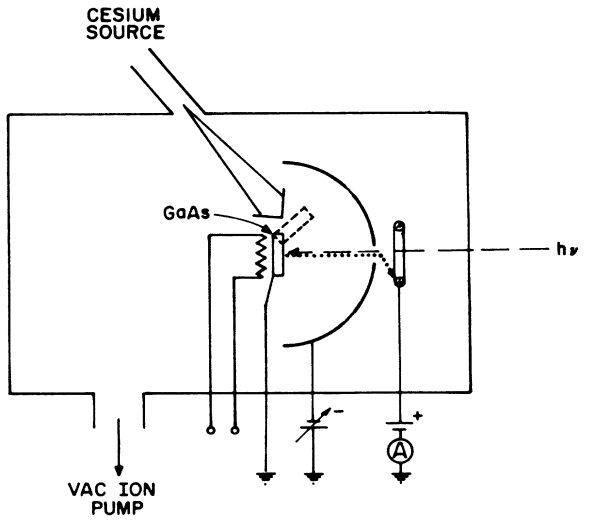

FIG. 1. Experimental setup.

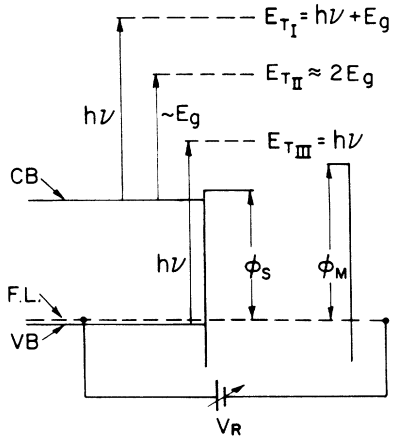

FIG. 2. Energy-level diagram for the electron-emission experiment (shown with $V_R = 0$).

conduction-band–to–acceptor transitions. The photoluminescent efficiency was not determined.

As shown in Fig. 1, the GaAs specimen forms the cathode of a triode. A ring-shaped anode collects the electrons transmitted by the axial aperture in the dome-shaped electrode which acts as a grid. The hemispherical configuration was chosen to select those electrons which leave the specimen with a velocity vector most nearly normal to the surface. A fine wire mesh covers the aperture to preserve the hemispherical field distribution. Radiation to generate electron-hole pairs in the specimen was introduced through the ring-shaped anode and the aperture in the dome.

A retarding potential was applied to the dome electrode (negative by a voltage V_R with respect to the GaAs cathode) thus selecting the energy of those electrons which are to reach the anode. Therefore, the current to the anode consists of electrons whose total energy is greater than $qV_R + \Phi_M$, where q is the electron charge and Φ_M the work function of the dome electrode (Fig. 2).

The anode current was measured with a Keithley electrometer at various values of V_R. The integrated velocity distribution of the emitted electrons is given by

$$I = \int_{qV_R + \Phi_M}^{\infty} N(E)dE,$$

where $N(E)$ is the number of electrons having an energy E.

To find the total number of electrons emitted by the specimen, the dome is tied to the anode and both these electrodes are biased positively to collect all the emitted electrons. From geometrical considerations (area of axial aperture is 10^{-2} cm^2 in dome having a 2-cm radius), it was estimated that a fraction of 4×10^{-4} of the emitted electrons can be transmitted to the collector ring. This factor was verified experimentally as well.

The small contribution to the collector current from the dome electrode due to scattered radiation was measured by connecting the collector to the specimen and biasing these two surfaces positively with respect to the dome. This component was then subtracted from the collector current.

The specimen was irradiated with the focused output of a Perkin-Elmer monochromator using a tungsten-ribbon lamp as the source of radiation ($h\nu > E_g$).

As shown in Fig. 2, the incident radiation can excite directly an electron from the valence band to energies higher than the work function of this dome. The reference energy is taken to be zero at the valence-band edge. The incident photon of energy $h\nu > E_g$ can excite an electron from the valence band to a maximum total energy of $h\nu$; and, at sufficiently high excitation, when the electron concentration in the conduction band is appreciable, the incident photon can excite a conduction-band electron to a total energy of $h\nu + E_g$. For the sake of simplicity, the above arguments neglect the additional energy required to conserve momentum.

Although a variety of Auger transitions can occur,[7] we shall be concerned only with those resulting in a hot electron. These are transitions from the conduction band or the donors to the valence band or to the acceptors. Since typical activation energies for donors and acceptors in GaAs are, respectively, 5 and 30 meV, the highest possible kinetic energies of Auger hot elec-

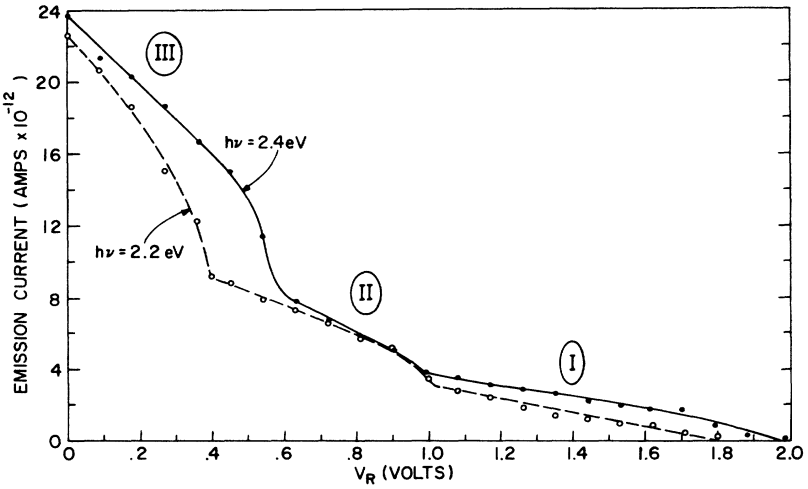

FIG. 3. Anode current versus retarding potential for two excitation energies.

trons range from 1.43 eV for the band-to-band transition to 1.40 eV for the donor-acceptor transition. The difference of ~0.03 eV is comparable to our experimental resolution in the measurement of the energy distribution of emitted electrons. Therefore, we cannot distinguish between the detail of band-to-band, exciton, band-to-acceptor, or residual donor-to-acceptor transitions which generate the hot Auger electrons.

Figure 3 shows the results of a plot of anode current versus retarding potential for two different optical excitation energies. Each curve consists of three components indicating the successive uncovering of three processes as the retarding potential is decreased from $V_R = 2.0$ V to allow the collection of less energetic electrons. We shall label these regions I, II, and III; and we shall show that it is in region II that the emission of Auger electrons is believed to occur. Note also that the thresholds for the onset of the dominant processes in regions I and III shift to higher values of retarding potential as the photon energy is increased whereas the threshold for the onset of the Auger effect (region II) remains stationary. The shift in threshold is approximately equal to the change in photon energy (0.2 eV). The work function of the cesiated aluminum dome, Φ_M, and also of the anode is known from previous determination to be 1.8 eV. Therefore, the dome blocks all electrons whose total energy is less than $qV_R + 1.8$ eV. Now we can sort out the three processes of Fig. 3.

The strongest contribution, region III, corresponds to the direct optical excitation of the abundant valence-band electrons. Its highest energy threshold occurs at $qV_{R_{III}} = h\nu - \Phi_M$ and shifts with the energy $h\nu$ of the exciting photon.

Region II corresponds to the Auger excitation of conduction-band electrons. The highest energy threshold for region II occurs at $qV_{R_{II}} = 2E_g - \Phi_M = 1.0$ eV and does not shift with the energy $h\nu$ of the exciting photon. It is conceivable that region II might correspond to electrons excited by the reabsorption of across-the-gap radiative recombination. However, this contribution is negligible because of the combination of a relatively low photon density and the low capture cross section for free electrons.[8]

The weakest contribution, region I, is tentatively attributed to the optical excitation of conduction-band electrons by the relatively intense incident radiation. The highest energy threshold for this process is $qV_{R_I} = E_g + h\nu - \Phi_M = h\nu - 0.4$ eV; therefore, it varies with the photon energy.

The dependence of the intensity of the three processes on the intensity of the exciting radiation is tabulated in Table I. These data were obtained as follows: The extrapolation of region II to $V_R = 0$ was subtracted from the value of region III at $V_R = 0$ (Fig. 3), and the extrapolation of region I to $V_R = 0$ was subtracted from the extrapolation of region II to $V_R = 0$ to isolate the contribution of each process at $V_R = 0$. The extrapolations to $V_R = 0$ assume a linear dependence on V_R in the region of extrapolation.

The direct excitation of electrons from the valence band draws from a constant reservoir of electrons; therefore, the contribution to the emission current is proportional to the intensity of the exciting radiation, as observed (see Table I).

The Auger electrons result from the interac-

Table I. Intensity dependence of the three emission processes at $V_R = 0$.

N_A (cm^{-3})	$h\nu$ (eV)		Excitation from Conduction Band L_o (μW)	I_I (pA)	I_{II} (pA)	I_{III} (pA)	"Auger" Emission $I_{II}-I_I$ (pA)	Excitation from Valence Band $I_{III}-I_{II}$ (pA)
8×10^{16}	2.20		15	9.0	20.5	37.3	11.5	16.8
			10	6.6	12.2	22.6	5.6	10.4
		Ratio	1.5	1.4			[2.1]	1.6
		$(\text{Ratio})^2$	[2.26]					
2×10^{17}	2.20		23	14	2.5	62	11	37
			10	5.5	7.5	22.5	2.0	15
		Ratio	2.3	2.5			[5.5]	2.5
		$(\text{Ratio})^2$	[5.3]					
2×10^{17}	2.45		12	5.2	15.5	24.4	10.3	8.9
			7	3.5	8.5	13.8	3.0	5.3
		Ratio	1.7	1.5			[3.5]	1.5
		$(\text{Ratio})^2$	[2.9]					

tion of two electrons with one hole. The hole concentration is nearly constant whereas the electron concentration is proportional to the intensity L_0 of the incident radiation. Therefore, the Auger contribution to the emission current should increase as L_0^2, which agrees with observation.

The direct optical excitation of conduction-band electrons should also increase as L_0^2 since the number of electrons in the conduction band is proportional to L_0 and the probability of optically exciting these carriers is also proportional to L_0. The observation, however, is that the intensity of process I is roughly proportional to the excitation rate. We have no definitive explanation for this apparent anomaly.

In summary, the Auger electrons emitted into vacuum are characterized by a velocity distribution which does not depend on the energy of the exciting photons; the Auger emission current varies as the square of the excitation rate.

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