Hot-electron luminescence: A comparison of GaAs and InP

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A detailed study of the properties of hot-electron luminescence at $T=2$ K in lightly p-type GaAs and InP is presented. First, substantial changes are observed in the spectra as the angle between the incident laser electric field and the crystal axes are varied. The combination of the spherical nature of the acceptor wave function (i.e., the wave function of the hole bound at the acceptor) and the strong anisotropy of the heavy-hole valence band are shown to be the causes of the changes. Second, hot luminescence spectra in GaAs and InP are compared as a function of laser energy. The relative changes in the intensity of these spectra give a detailed picture of the k-space dependence of the acceptor wave function, and further provide a determination of intervalley scattering times in GaAs. This last measurement is compared with previous measurements and calculations of intervalley scattering times.

I. INTRODUCTION

In 1981, it was reported that nonequilibrium ("hot") electrons radiatively recombine at neutral acceptors to produce a highly structured spectrum.[1] This hot (e, A^0) luminescence has since been used as a probe of hot-electron kinetics,[2-4] band structure,[5,6,13] and the coupled electron-phonon plasmon.[7] Recently, an electroluminescent device has also been observed to emit hot (e, A^0) luminescence.[8]

The process by which hot (e, A^0) emission is generated is shown in Fig. 1. Experiments must be performed at low temperatures (2 K for the data presented in this paper), where the acceptors are all neutral. The doping level is kept low enough ($\leq 2\times10^{17}$ cm^{-3}) so that the acceptors may be considered isolated. Then, because the hole bound to the acceptor has a wave function localized in real space [$\simeq 21$ Å in GaAs (Ref. 9)], the wave function is spread out in k space. Therefore, it is represented as a dashed line in Fig. 1. If the injected carrier density is low enough so that carrier-carrier scattering can be ignored ($\leq 10^{16}$ cm^{-3}),[4] then a typical spectrum (Fig. 2) is linear with laser power and consists of peaks corresponding to initial monoenergetic populations of electrons losing energy by the sequential emission of LO phonons. (The fraction of electrons emitting the hot luminescence is always negligible, so the presence of the acceptors does not in any way alter the electron kinetics.)

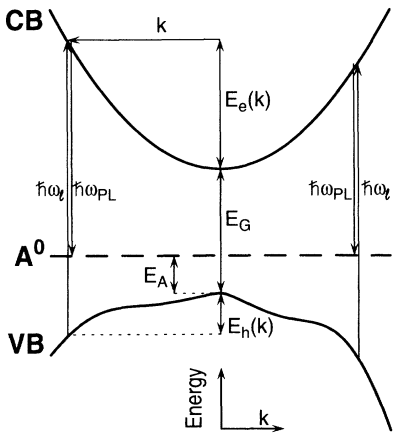

FIG. 1. Schematic of the excitation and emission process for the highest-energy peak in the hot (e, A^0) spectrum. The valence band is shown as warped, to illustrate the different energies of the hot luminescence for different directions in k space.

This paper will concentrate on the highest-energy peak in the spectra. The majority of experiments using hot, (e, A^0) luminescence have depended upon an analysis of this peak as some experimental parameter (laser energy, magnetic field, injected carrier density) is varied. This peak corresponds to electrons generated from the heavy-hole (HH) valence band which have yet to scatter from their initial state. As the laser photon energy is increased, the initial kinetic energy and wave vector of these electrons increases. Therefore, by simply changing the laser energy, a different wave vector is probed.

In some cases, different groups have used different techniques [but all based on hot (e, A^0) luminescence] to study the same phenomenon (e.g., intervalley scattering[2,3,5] in GaAs), and have arrived at conflicting results.

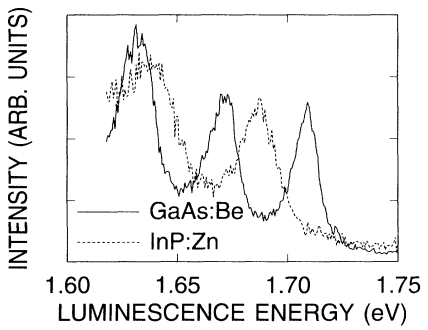

FIG. 2. Hot-luminescence spectra for GaAs:Be ($p=7\times10^{16}$ cm^{-3}) and InP:Zn ($p=2\times10^{17}$ cm^{-3}). The laser energy was 1.7519 eV.

The interpretation of the hot-luminescence spectra in these various experiments has made implicit or explicit assumptions about the recombination process, some of which have not been verified. Here the hot (e, A^0) emission will be studied in detail in order to clarify some of these assumptions.

The paper is organized as follows: In Sec. II, measurements of the polarization of hot (e, A^0) luminescence will be given, which will show that the acceptor wave function extends nearly spherically in all directions in k space. The polarization measurements also directly reveal the warping of the heavy-hole valence band. In Sec. III, the hot (e, A^0)-luminescence intensity in GaAs and InP will be compared to show that the effective-mass approximation[10] gives a good representation of the wave function of the hole bound to a shallow acceptor for values of k between zero and 15% of the Brillouin-zone edge. The comparison of bulk GaAs and InP for slightly larger values of k gives a means of determining intervalley scattering in GaAs, which will be shown in Sec. IV. A brief discussion of previous measurements of intervalley scattering in GaAs will also be given there. Section V will summarize the paper.

II. THE ACCEPTOR WAVE FUNCTION AND VALENCE-BAND WARPING

In GaAs and InP, the structure of the lowest conduction-band minimum near $k=0$ is essentially spherical and well described by the effective-mass approximation. Thus, one expects that the wave function of an electron bound at an isolated donor (D^0) is hydrogenlike. For a hole bound to an acceptor (A^0), the situation is not as simple. The presence of HH and light-hole (LH) valence bands, plus the substantial warping (anisotropy) of the HH band, may lead to a wave function for this bound hole (which will be referred to as an acceptor wave function) that deviates significantly from a hydrogenic form. Indeed, Zakharchenya *et al.*[2] have suggested that, for $|ka_0| \gg 1$ [a_0 is the radius of the acceptor wave function, 21.3 Å in GaAs (Ref. 9)], the acceptor wave function is strongly concentrated in the [111] direction, i.e., the direction of heaviest mass. On the other hand, the experiments involving hot (e, A^0) emission have been in the wave-vector range $|ka_0| \leq 2.5$, where, as we will show, the effective-mass approximation still gives a good representation of the wave function.

In this section, polarization measurements of hot (e, A^0) luminescence will be presented that will clearly demonstrate that the acceptor wave function extends in all directions in k space at least for $|ka_0| \leq 1.7$, with no evidence of the strong concentration in the [111] direction. The implication of the present data on the interpretation of earlier experiments will be considered at the end of this section.

In order to understand the data, it is first necessary to review the matrix elements governing the polarization of hot (e, A^0) emission. Here, we will only summarize results[2] for GaAs grown in the usual [100] orientation. The calculations are for normal incidence in a backscattering geometry, which experimentally is the most accessible. The linearly polarized electric field of the incident laser $\mathcal{E}_l$ is chosen to lie along either a [110] axis (a cleavage edge) or at 45° to the cleavage edge along a [100] axis. The degree of polarization ρ is defined in the usual way as

$$\rho=(I_{\parallel}-I_{\perp})/(I_{\parallel}+I_{\perp}) , \tag{1}$$

where $I_{\parallel}$ is the luminescence intensity polarized parallel to the incident laser and $I_{\perp}$ is the luminescence intensity polarized perpendicular to the incident laser. The degree of linear polarization will depend upon the direction of the wave vector **k** of the photocreated electron-hole pairs and also upon which valence band is involved. The highest-energy peak in the hot (e, A^0) spectrum comes from the heavy-hole valence band. For this valence band, for carriers in high-symmetry directions, the results for the degree of polarization are summarized in Table I.

In particular, from Table I, note that for a laser beam with $\mathcal{E}_{l\parallel}$ [100], if we measure both $I_{\parallel}$ and $I_{\perp}$, and then plot the *difference* $I_{\parallel}-I_{\perp}$, then this difference spectrum will have *no* contribution from carriers in [111] directions, and only a small contribution from [110] carriers. The main contribution will be from carriers with **k** in [100] directions. Similarly, for $\mathcal{E}_{l\parallel}$ [110], the difference spectrum will have *no* contribution from carriers in [100] directions, and only a small contribution from [110] carriers. For this geometry, the main contribution will be from carriers with **k** in [111] directions.

Because of warping, the heavy-hole mass in the [111] directions $(0.92m_0)$ is larger than the mass of the heavy

TABLE I. Calculated (Ref. 2) degree of linear polarization [Eq. (1)] for hot (e, A^0) emission for electrons excited from the heavy-hole $(J=\frac{3}{2}, m_J=\pm\frac{3}{2})$ valence band for various directions in k space for two different laser polarizations. These results are valid for any direct-gap zinc-blende-structure semiconductor excited in normal incidence with the emission collected in backscattering. The sample surface is assumed to be a (100) plane.

Incident laser polarization along \ Direction of electron and hole momentum	[100]	[110]	[111]
		Degree of linear polarization	
[110]	$\frac{1}{3}$	$\frac{1}{11}$	0
[110]	0	$\frac{1}{19}$	$\frac{1}{4}$

hole in the [110] directions ($0.66m_0$) or the [100] directions ($0.39m_0$).[11] Therefore, for fixed laser photon energy $\hbar\omega_l$, the energy of hot (e, A^0) emission from carriers in the [111] directions will be at the highest energy, with the emission from carriers in [100] directions at the lowest energy. Figure 1 schematically, illustrates this effect. Carriers in [110] directions and, indeed, in any other directions, will generate hot (e, A^0) emission at an energy between that of [111] carriers and [100] carriers.

An experimental test of the ideas of the previous two paragraphs is shown in Fig. 3, where measured difference spectra $I_{\parallel} - I_{\perp}$ are shown for $\mathcal{E}_l$ either along [110] or [100]. As predicted from Table I, for $\mathcal{E}_{l\parallel}$ [100], the highest-energy peak in the difference spectrum is at lower energy than the same peak for $\mathcal{E}_l \parallel$ [110]. We can determine the energies E_e and E_h of the hot electrons and holes corresponding to the energy $\hbar\omega_{\rm PL}$ at the peak of one of these difference spectra from energy conservation. By inspection of Fig. 1,

$$E_e = \hbar\omega_{\rm PL} - (E_G - E_A) \tag{2}$$

and

$$E_h = \hbar\omega_l - \hbar\omega_{\rm PL} - E_A \ , \tag{3}$$

where E_G is the band-gap energy and E_A is the binding energy of the acceptor. From the measured dispersion of the conduction band,[12] we determine the magnitude of the corresponding wave vector k, so that we have determined a single point of the relation between E_h and k. Then, from a family of such difference spectra taken at different laser photon energies, we can map out the hole dispersion for the two different geometries $\mathcal{E}_l \parallel [100]$ and $\mathcal{E}_l \parallel [110]$. The resulting dispersion curves (Fig. 4) are close to, and between, the theoretical dispersion curves[11] in the [111] and [100] directions, in accord with the previous discussion. With an appropriate line-shape-fitting procedure one could, in principal, determine the valence-band dispersion in the high-symmetry directions from these spectra. Such a procedure has recently been used to measure the valence-band dispersion,[6] including warping,[13] in a series of $GaAs/Al_xGa_{1-x}As$ quantum wells. The presence of three high-symmetry directions in the bulk, as compared to only two high-symmetry directions in a quantum well, makes the line-shape fitting in the bulk substantially more difficult and less accurate than in a quantum well, so we will not attempt it here.

Nonetheless, the ability to observe hot (e, A^0) luminescence from carriers at different directions in k space does give us a further opportunity to test the spherical nature (or lack thereof) of the acceptor wave function. Clearly, the hypothesis that the wave function is fully concentrated in the [111] directions is contradicted by the data of Fig. 3 for the $\mathcal{E}_l \parallel [100]$ geometry. These data show that there is a significant hot (e, A^0) signal even when the contribution from carriers in [111] directions is suppressed. Because of the larger hole mass in the [111] directions as compared to the [100] directions, the density of hole states in a [111] direction is about four times

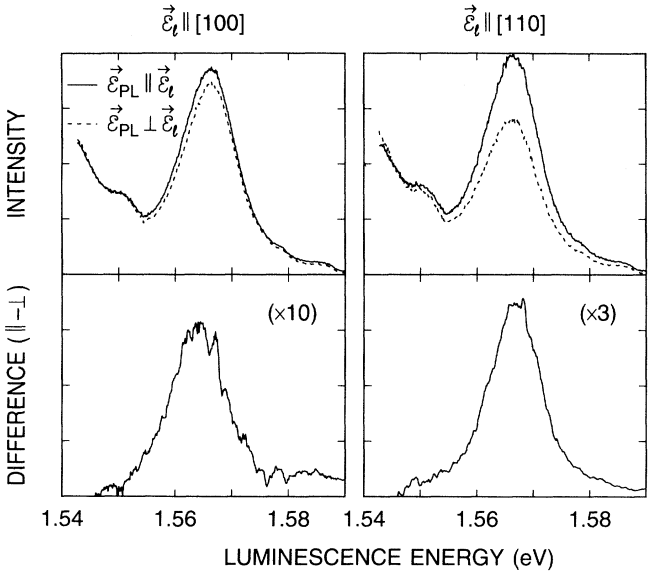

FIG. 3. Hot-luminescence spectra (upper panels) and their differences (lower panels) for the two scattering geometries with laser polarizations $\mathcal{E}_l \parallel [100]$ (right-hand panels) and $\mathcal{E}_l \parallel [110]$ (left-hand panels). The sample was GaAs:C ($p = 1.5 \times 10^{17}$ cm^{-3}) and the laser energy was 1.5978 eV. Note that the two difference spectra peak at slightly different energies; this peak shift is due to the warping of the heavy-hole valence band.

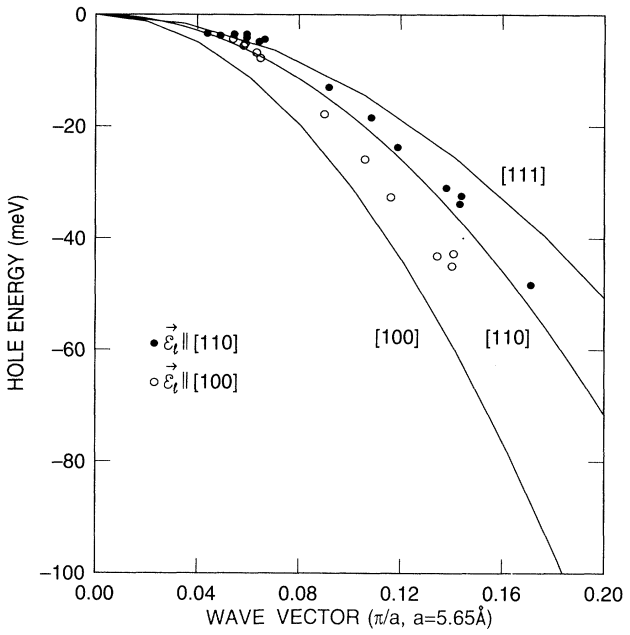

FIG. 4. Points represent the valence-band dispersion in GaAs derived from hot-luminescence spectra using Eqs. (2) and (3). Here, $\hbar\omega_{\rm PL}$ is taken as the peak position from difference spectra such as those in the lower panels of Fig. 3, for a series of laser energies. The curves represent the calculated valence-band dispersions (Ref. 11) in the high-symmetry directions, using a nonlocal pseudopotential. For the range of wave vector shown, the nonparabolicity of the heavy-hole valence band is negligible. The effective masses of the three directions are 0.388, 0.656, and 0.920, in units of m_0.

larger than in a [100] direction. Let us suppose that the acceptor wave function is spherical, i.e., its magnitude depends only upon the magnitude of **k**, not the direction. Then we would expect the difference spectrum for the geometry $\mathcal{E}_l \| [110]$ (i.e., the signal primarily from electrons in [111] directions) to be about four times stronger than the difference spectrum for the $\mathcal{E}_l \| [100]$ geometry (which is primarily from [100] electrons).[14] The data of Fig. 3, taken for a laser energy corresponding to $|ka_0| = 0.79$, show that the difference in intensity between the two geometries is about a factor of four, which indicates that the acceptor is nearly spherical at this wave vector. (The exact agreement is probably fortuitous.) As the laser energy is increased to 1.7510 eV, corresponding to $|ka_0| = 1.70$, the intensity ratio increases to about 6. This small increase could be due to a slight anisotropy in the acceptor at this higher wave vector. Another possibility, however, is a slight mixing of the heavy- and light-hole bands, which would be expected to be somewhat stronger for the lighter-mass [100] directions than for the [111] directions.

We conclude that the acceptor in this range is nearly spherical, with a possible slight deviation from exactly spherical. Interpretation of experimental data with the assumption that the acceptor is extremely nonspherical is questionable, while an analysis that implicity assumes a precisely spherical acceptor[5] must also be examined carefully to see how the results are altered if the acceptor is not exactly spherical.

III. THE EFFECTIVE-MASS APPROXIMATION FOR ACCEPTORS

In Sec. II, polarization studies of hot (e, A^0) emission demonstrated that the acceptor is generally spherical in nature. In this section, we will compare hot (e, A^0) emission in GaAs and InP, as well as several different acceptors in GaAs, to demonstrate that the effective-mass approximation (EMA) gives a good description of the wave-vector dependence of the acceptor wave function.

Under the EMA, the k-space dependence of the acceptor wave function (actually the wave function of the hole bound to the acceptor) is[15]

$$|M(k)| \propto (1 + a_0^2 k^2)^{-2} , \tag{4}$$

where a_0 is the Bohr radius of the acceptor. From Fermi's golden rule, the luminescence intensity I from hot electrons of wave vector **k** recombining at a neutral acceptor is

$$I \propto n |M(k)|^2 \tau , \tag{5}$$

where n is the number of hot electrons and τ is the length of time before the hot electron is inelastically scattered. (Recall that only a tiny fraction of the hot electrons actually recombine at an acceptor before scattering.)

Baldereschi and Lipari[10] have shown that the EMA describes the energy levels of acceptors in GaAs, provided the proper effective mass is chosen. This value of effective mass [0.310 for GaAs (Ref. 9)] falls between the HH and LH masses, and leads to a Bohr radius $a_0 = 21.3$ Å. Here, the measured intensity of the highest energy peak of the hot (e, A^0) spectrum will be compared with Eqs. (4) and (5). The intensity of the measured spectra will be found to be well described by this straightforward calculation. In a previous study in GaAs,[16] our results were also in accord with Eq. (4). A disadvantage of the technique used there, however, was that an accurate calibration of the quantum efficiency of the detection system was required over a fairly broad range of photon energies. Also, small corrections due to the changing absorption depth and nonparabolicity were ignored. Here we avoid these difficulties by making a comparison of GaAs and InP, instead of an absolute measurement of GaAs. When comparing GaAs and InP, the ratio of the hot-luminescence intensity in the two materials is measured, avoiding the need for an absolute calibration of the quantum efficiency of the detection system. Further, because of the similarity of the band structures of these two materials, the small corrections that might be needed for an absolute measurement will tend to cancel when the ratio is taken.

Before comparing GaAs to InP, we will first compare several acceptor dopant species in GaAs to show that, as expected for a shallow acceptor, the specific dopant has no measurable effect on the acceptor wave function for the range of wave vectors investigated here ($a_0 k \leq 2.6$). The integrated intensity of the highest-energy peak in the hot (e, A^0) spectrum was measured as a function of laser energy for several GaAs samples doped with different acceptors (C, Be, Mg, Zn). Dopants were compared pairwise by taking the ratio of the integrated intensity, normalizing out any drift in the laser power. For each comparison, to within the $\pm 5\%$ error in the measurement, the ratio did not change as the laser energy was changed over the range 1.6–2.0 eV. These comparisons show that the acceptor wave function is the same for all of these dopants. The wave vector corresponding to the highest laser energy used in the comparisons corresponds to 20% of the Brillouin-zone edge. We conclude that central-cell corrections to the acceptor wave function are negligible for this range of wave vector. The acceptors can be taken as shallow for these hot luminescence experiments.

We now compare the acceptor wave function in InP to that of GaAs. The Bohr radius for shallow acceptors is smaller in InP (13.5 Å) (Ref. 17) than in GaAs (21.3 Å).[9] Thus, we expect the k-space acceptor wave function to be spread out farther in InP than in GaAs. When we compare the intensity of the hot (e, A^0) luminescence in InP and GaAs, we see from Eq. (5) that changes in the ratio could be due to n, $|M|$, or τ. Changes in density n are accounted for by normalizing against the incident laser photon flux. Then we can drop the density dependence in Eq. (5).[18] If we measure the intensity I (integrated area) of the highest-energy peak in the hot (e, A^0) spectrum, then

$$\frac{I_{\mathrm{GaAs}}}{I_{\mathrm{InP}}} = \frac{|M_{\mathrm{GaAs}}|^2 \tau_{\mathrm{GaAs}}}{|M_{\mathrm{InP}}|^2 \tau_{\mathrm{InP}}} . \tag{6}$$

The hot-electron inelastic lifetime can depend on electron energy E_e and carrier density. At low density ($\leq 10^{16}$

cm^{-3}), always the case here, carrier-carrier scattering effects are unimportant[4] and τ is independent of density. The lifetime τ will be determined by phonon scattering and will, in general, depend on E_e. However, provided E_e is greater than about three times the LO-phonon energy, but less than the threshold for intervalley scattering ($\simeq 0.3$ eV in GaAs, 0.9 eV in InP), then the dominant contribution to τ will come from the polar emission of LO phonons.[19] (We are at low temperature, so phonon absorption is negligible.) In this energy range, τ is nearly constant in both materials, and the small increase in τ with energy is nearly identical for the two materials. Therefore, from Eq. (6), changes observed in the ratio $I_{\mathrm{GaAs}}/I_{\mathrm{InP}}$ in the range $0.1\ \mathrm{eV} \leq E_e \leq 0.3$ eV are due entirely to changes in the ratio $|M_{\mathrm{GaAs}}|^2/|M_{\mathrm{InP}}|^2$. If the acceptors are effective-mass-like, then the matrix elements are given by Eq. (4).

To test the validity of Eq. (4), $I_{\mathrm{GaAs}}/I_{\mathrm{InP}}$ is measured at a series of laser energies $\hbar\omega_l$. As noted earlier, changing $\hbar\omega_l$ changes the hot-carrier wave vector k. Because of band-structure differences, k will be somewhat different in InP and GaAs for the same $\hbar\omega_l$. We determine k for each material as follows. When we measure the integrated intensity I of the highest-energy peak in the hot-luminescence spectrum, we also determine the photoluminescence energy $\hbar\omega_{\mathrm{PL}}$ corresponding to the peak. From Eq. (2), we determine the equivalent electron energy E_e. From E_e we can determine the wave vector k from[20]

$$\hbar^2 k^2/2m^* = E_e(1+|\alpha|E_e)\ , \tag{7}$$

where m^* is the band-edge effective-electron mass ($0.067m_e$ for GaAs and $0.0803m_e$ for InP) and $|\alpha|$ represents the nonparabolicity. For GaAs, $|\alpha|$ has recently been determined to be 0.75 from magneto-Raman measurements.[12] No comparable measurements exist for InP, but from $\mathbf{k}\cdot\mathbf{p}$ theory, we expect a similar value for the nonparabolicity in InP. We will therefore take $|\alpha|=0.75$ in InP also, and note that there are no significant changes in our results for $\pm 20\%$ changes in this parameter. In fact, as long as $|\alpha|$ is chosen to be similar for the two materials, we do not find substantial changes in our results.

Applying the value of k determined by Eq. (7) in Eq. (4), we can compute the ratio $|M_{\mathrm{GaAs}}|^2/|M_{\mathrm{InP}}|^2$ at each laser energy and compare the result to the measured intensity ratio. The result is shown in Fig. 5. In this section, we will only discuss results for electron energies in GaAs that are below the threshold for intervalley scattering. As the electron energy and wave vector are increased above this threshold, the onset of intervalley scattering will decrease τ for GaAs. Thus, at energies above the threshold, the measured intensity ratio will not simply be proportional to $|M_{\mathrm{GaAs}}|^2/|M_{\mathrm{InP}}|^2$. In the next section, it will be shown that effects of intervalley scattering are indeed observed in the data at these higher energies.

The agreement shown in Fig. 5 is very good below the intervalley-scattering threshold. Both the measured intensity ratio and the result predicted from Eqs. (4)–(6)

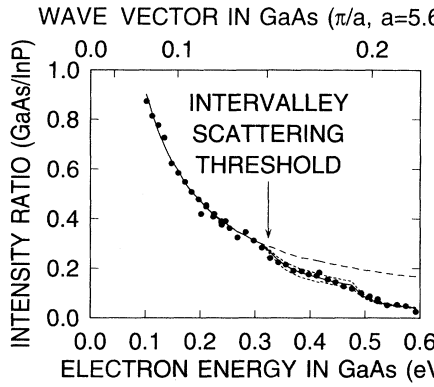

FIG. 5. The points are the ratio of the measured integrated intensity of the highest-energy peak in hot (e, A^0) spectra for GaAs:Be ($p=7\times10^{16}$ cm^{-3}) and InP:Zn ($p=2\times10^{17}$ cm^{-3}). The calculations (curves) are described in the text.

decrease by a factor of 3.5 over this range. We remark that the absolute changes in the individual values of $|M|^2$ are more than an order of magnitude over the same range. Dymnikov, Perel, and Polupanov[21] have proposed an alternate expression for $|M|^2$ that derives from considering the acceptor as consisting of both a heavy-hole part and a light-hole part. This alternate expression gives a significantly smaller change in the intensity ratio, predicting a decrease of only a factor of 2.6, which is inconsistent with the observed change. We summarize the results of this section and the preceding section with the conclusion that spherical effective-mass theory provides a good description of the acceptor wave function in InP and GaAs for common shallow-acceptor dopants over the wave-vector range studied here.

IV. INTERVALLEY SCATTERING IN GaAs

In the preceding section, we showed that shallow acceptors in GaAs and InP can be described using effective-mass theory. In our analysis of the data, we worked at electron energies where the hot-electron inelastic lifetime τ was the nearly constant LO-phonon polar emission time $\tau_{e\text{-LO}}$. Once the energy of the hot electrons exceeds the threshold for scattering to a satellite valley, τ is influenced both by LO-phonon emission and intervalley scattering:

$$\tau^{-1} = \tau_{e\text{-LO}}^{-1} + \tau_{\Gamma\text{-}L}^{-1} + \tau_{\Gamma\text{-}X}^{-1}\ , \tag{8}$$

where $\tau_{\Gamma\text{-}L}$ is the scattering time from the Γ valley to the four equivalent L valleys and $\tau_{\Gamma\text{-}X}$ is the scattering time from the Γ valley to the six equivalent X valleys. In InP, the L valleys are more than 0.8 eV above the Γ minimum, and the X valleys are even higher. Therefore, in the present experiments, the electron energy is never large enough to allow intervalley scattering in InP, and $\tau=\tau_{e\text{-LO}}$. For GaAs, however, the Γ-L separation is $E_L=0.296$ eV and the Γ-X separation is $E_X=0.46$ eV. Here, the absorption of visible photons can generate electrons with sufficient energy to scatter the satellite valleys.

At low temperatures, the rate of scattering to a given valley depends on the density of final states in the satellite valley. Assuming roughly parabolic satellite valleys, the intervalley scattering time can be written as[22]

$$\tau_{\Gamma\text{-}L}=\tau^0_{\Gamma\text{-}L}[(E_e-E_L-\hbar\omega_{ze})/\hbar\omega_{ze}]^{-1/2} \tag{9}$$

for scattering to the L valleys. Here, $\hbar\omega_{ze}$ is an average zone-edge phonon energy, taken as 28 meV.[23] The parameter $\tau^0_{\Gamma\text{-}L}$ is proportional to the inverse square of the effective deformation potential[24] $D_{\Gamma\text{-}L}$, which is often used to characterize intervalley scattering. A similar expression can be written for scattering to the X valleys. The relation between $\tau^0_{\Gamma\text{-}L}$ and the effective $D_{\Gamma\text{-}L}$ depends on assumptions about the band structure and which phonons participate in the scattering. Since the experiments measure scattering times, we will mainly discuss our results as times, except when comparing our measurements to theoretical calculation of the deformation potential.

Equation (8) may be substituted into Eq. (6) to obtain

$$\frac{I_{\rm GaAs}}{I_{\rm InP}}=\frac{|M_{\rm GaAs}|^2}{|M_{\rm InP}|^2}\frac{\tau^{\rm GaAs}_{e\text{-LO}}}{\tau^{\rm InP}_{e\text{-LO}}} \times\frac{1}{1+\tau^{\rm GaAs}_{e\text{-LO}}/\tau_{\Gamma\text{-}L}+\tau^{\rm GaAs}_{e\text{-LO}}/\tau_{\Gamma\text{-}X}} . \tag{10}$$

In Fig. 5, we show the measured intensity ratio and the ratio calculated utilizing Eq. (10) and the matrix elements of the preceding section. We again take $\tau^{\rm GaAs}_{e\text{-LO}}/\tau^{\rm InP}_{e\text{-LO}}$ to be constant. The dashed curve assumes no intervalley scattering, i.e.,

$$\tau^{\rm GaAs}_{e\text{-LO}}/\tau_{\Gamma\text{-}L}=\tau^{\rm GaAs}_{e\text{-LO}}/\tau_{\Gamma\text{-}X}=0 .$$

The solid curve includes intervalley scattering with $\tau^0_{\Gamma\text{-}L}/\tau^{\rm GaAs}_{e\text{-LO}}=4.35$ and $\tau^0_{\Gamma\text{-}X}/\tau^{\rm GaAs}_{e\text{-LO}}=0.82$. Changing $\tau_{\Gamma\text{-}L}$ by $\pm30\%$ will produce a noticeable disagreement with the data in Fig. 5, as shown by the dotted curves.

The largest source of systematic error in this determination of $\tau_{\Gamma\text{-}L}$ is the assumption that the fraction of hot electrons generated from the heavy-hole valence band [which are the only electrons that contribute to the highest-energy (e,A^0) peak] is constant. InP has a much smaller spin-orbit splitting than GaAs, 0.108 eV vs 0.33 eV.[11] In InP, for the electron energies considered here, electrons can always be generated from the split-off valence band. In GaAs, absorption due to the split-off band commences at a laser energy slightly lower than the threshold for intervalley scattering. Therefore, the fractional absorption from the split-off band for the range $E_e\gtrsim0.3$ eV in Fig. 5 is increasing more rapidly for GaAs than for InP. By ignoring this relative change between InP and GaAs in the fractional split-off absorption, an intervalley scattering time shorter than the actual time is observed. Based on band-edge masses, split-off absorption is at most 15% of the total, leading to at most a 40% increase in $\tau_{\Gamma\text{-}L}$. As to errors in our determination of $\tau_{\Gamma\text{-}X}$, they will be somewhat larger than those for $\tau_{\Gamma\text{-}L}$, as errors in both $|M_{\rm GaAs}|^2/|M_{\rm InP}|^2$ and intervalley scattering to the L valley will tend to accumulate as we extrapolate to higher electron energies. The Γ-X scattering time derived from this data is probably valid only to within a factor of 2. To put this error in perspective, note that the problem of error accumulation is common to the previous measurements[3,5,25,26] of $\tau_{\Gamma\text{-}X}$. In any case, the present experiments confirm that when the electron energy is greater than about 0.5 eV, scattering to the X valley will predominate.

Taking $\tau^{\rm GaAs}_{e\text{-LO}}=190$ fsec,[27] the intervalley scattering times obtained here are in good agreement with our earlier determination of these quantities, and also with the $T=300$ K results for $\tau_{\Gamma\text{-}L}$ obtained by Shah *et al.*[28] (when appropriate adjustment for the temperature dependence of $\tau_{\Gamma\text{-}L}$ arising from the various phonons that actually contribute to intervalley scattering is made[24]).

To compare these measurements to the recent calculations of deformation potentials by rigid-ion pseudopotential methods,[11,29,30] we will use the connection between scattering times and effective deformation potential as discussed in Zollner, Gopalan, and Cardona.[24] The calculations are consistently somewhat lower ($D_{\Gamma\text{-}L}=3.0$–3.6 eV/Å) than that determined in this experiment ($D_{\Gamma\text{-}L}=4.8$ eV/Å). These theoretical deformation potentials are calculated for scattering between the exact high-symmetry Γ and L points. Taking into account[24] the lowered symmetry of the real intervalley scattering process, however, leads to a significant increase in the calculated value of the effective deformation potential, to $D_{\Gamma\text{-}L}=4.5$ eV/Å. Thus, it appears that the calculations and this measurement are in remarkably good agreement. On the other hand, there are several other experimental values of $D_{\Gamma\text{-}L}$ that are much lower or much higher than these values. A critical analysis of some of these experiments, summarized briefly here, has been presented elsewhere.[27] Many of these other experiments have required extensive calculations to obtain the intervalley scattering rates, where small changes in the model produced large changes in the derived scattering rate. Other experiments have strongly perturbed the sample with, for example, large magnetic fields. The critical analysis concluded that the correct value of the effective $D_{\Gamma\text{-}L}$ at low temperatures in GaAs is in the range 4–5 eV/Å, a conclusion which is further supported by the present experiment.

For scattering to the X valleys, the rigid-ion pseudopotential calculations give values of $D_{\Gamma\text{-}X}=3.0$–4.1 eV/Å. As in the case of scattering to the L valleys, accounting for the reduced symmetry of the actual scattering leads to a higher effective deformation potential of $D_{\Gamma\text{-}X}=6.5$ eV/Å. The value of $D_{\Gamma\text{-}X}=8$ eV/Å determined from these measurements agrees well with this value. Including the factor of 2 error estimated for $\tau_{\Gamma\text{-}X}$, we conclude $D_{\Gamma\text{-}X}=6$–11 eV/Å.

V. CONCLUSIONS

In this paper, we have examined the highest-energy peak of hot (e,A^0) luminescence in GaAs and InP in some detail. Based on polarization measurements, we have shown that the acceptor wave function is nearly spherical. These measurements also demonstrate the strong warping of the heavy-hole valence band, which is generic to all semiconductors with zinc-blende structure.

Measurements related to these polarization measurements have recently been reported by Hackenberg *et al.*[31] From intensity measurements of the emission, we verified that the effective-mass approximation provides a good description of the wave function of a hole bound to a shallow acceptor. The shallow acceptors investigated here (C, Be, Mg, Zn) were found to have identical wave functions. Comparing the intensity of the hot (e, A^0) luminescence in GaAs and InP also provided another means of determining the intervalley scattering rate in GaAs, from which we concluded $D_{\Gamma\text{-}L}=4-5$ eV/Å and $D_{\Gamma\text{-}X}=6-11$ eV/Å.

These experiments have shown that the commonly used description of acceptors in zinc-blende semiconductors is quantitatively accurate. Hot (e, A^0) emission has recently been demonstrated in acceptor-doped $GaAs/Al_xGa_{1-x}As$ quantum wells.[6,32] It will be of interest to extend the present measurements of the acceptor wave function to quantum wells. Since the three-dimensional Bohr radius of an acceptor is 21.3 Å, an examination of the acceptor wave function in quantum wells as the width is narrowed below about 50 Å should reveal the beginning of quasi-two-dimensional behavior for the acceptor.

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