Space- and time-resolved photoluminescence of In-alloyed GaAs using photoluminescence excitation correlation spectroscopy

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Photoluminescence excitation correlation spectroscopy is used to space and time resolve photoluminescence (PL) intensity variations in the region of isolated dislocations in as-grown In-alloyed GaAs. Spatially resolved PL maps show an annulus of high intensity with an inner and outer dark background surrounding a dislocation. Typical inner and outer diameters of the annuli are about 200 and 400 μm , respectively, which is smaller than the average dislocation separation in In-alloyed GaAs. Temporal resolution of the PL measures the carrier lifetime in the bright and dark regions. These measurements show that the lifetime variation accounts for the PL intensity variation. The variation of the lifetime with temperature indicates that the defects governing the lifetimes in the bright and dark regions are different. Moreover, both defects are deep and neither defect is EL2.

I. INTRODUCTION

Wafers of semi-insulating (SI) GaAs are widely used as substrates for the fabrication of GaAs high-speed digital integrated circuits (ICs) that use field-effect transistors (FETs). A critical part of the fabrication process is the formation of the active region under the gate of the FET. This region is formed by directly implanting dopant ions into the substrate and annealing. It is crucial that the properties of the activated region be uniform over the surface of the wafer, as otherwise large-scale integration is not possible. Commonly, arrays of field-effect transistors (FETs) are fabricated on the surface of the wafer to check the uniformity of the device characteristics over the wafer.¹⁻⁵ Variations are seen because of processing and due to initial nonuniformities in the substrate material.

In this work, the nonuniformities in the substrate material are studied. This topic has been the subject of much research. Variations of FET gate threshold voltages have been seen across the wafer. These are found to vary as the average density of dislocations in the substrate by some researchers, and with dislocation proximity by others.¹⁻⁵ The nature of the variation is also found to depend on the processing steps used in the activation anneal.^{3,4}

Much effort has been devoted to reducing the number of dislocations in as-grown substrates. At present, the most common GaAs substrate material is semi-insulating (SI) liquid-encapsulated Czochralski (LEC)-grown GaAs, which has an average dislocation density of 10^4 – 10^5 cm^{-2} , corresponding to an average separation of 50–15 μm .⁶ The substrate studied in this work is SI LEC In-alloyed GaAs, which has an InAs mole fraction of about 0.3%, which reduces the dislocation density over most of the area of a typical wafer to less than 10^2 cm^{-2} , or an average dislocation separation of 0.5 mm.⁶ There is much active research into other growth techniques.

There are many nondestructive techniques used to investigate the uniformity of substrates,⁷ including: x-ray topography, which is sensitive to crystallographic defects such as dislocations; IR imaging, which is sensitive to point defects, such as EL2, which absorb in the IR; scanning photoluminescence (PL), which is sensitive to variations in dopants and native defects; and cathodoluminescence (CL), which is similar to PL. These techniques are often done in combination with the more destructive techniques, which include: fabrication of an array of FETs over the substrate^{1,2,4,5}; fabrication of an array of devices for Hall measurements to measure sheet resistance over the substrate³; and etch pit density (EPD) measurements, which measure the dislocation density by using an etchant such as molten KOH to preferentially etch the dislocations.¹⁻⁶

Scanning PL is particularly well suited as a diagnostic tool because it is simple, relatively fast, and is sensitive only to about the top 1 μm of the substrate, as are the electrical devices themselves. Moreover, spectral information can give information concerning the defects present, and carrier lifetimes can be directly measured using time-resolved PL.

Much work has been done using scanning PL to map LEC GaAs substrates,⁷⁻¹⁰ showing variations in the near band-to-band PL intensity over two length scales, one over about 200 μm , the other over the entire wafer. The variation over the finer scale corresponds to PL imaging of the cellular structure formed by the dislocations in LEC GaAs.^{8,9} The intensity and carrier lifetimes vary by a factor of 2 over these features.⁹ Intensity of near band-to-band PL correlates with EPD across the wafer. Typically, both PL intensity and EPD vary with a characteristic "W" shape across the diameter of the wafer diameter.^{3,7-9} The dislocation densities vary from 10^4 to 10^5 cm^{-2} , while the near band-to-band PL typically varies by a factor of 3 over the wafer. Measurements of carrier lifetime made using time-resolved PL show variations in carrier lifetimes across the wafer, which correlate with PL intensity variations and etch-pit density. The lifetimes measured are between 200 and 500 ps at 5 K.⁹ The

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intensity of a 0.8-eV emission band associated with a trap is found to anticorrelate with the dislocation density, suggesting that a deep trap governs the lifetime. From this, it has been inferred that dislocations getter defects, which affect the lifetime of the material and hence the PL intensity.^{8,9} This explains the PL contrast near a dislocation, and an increase in intensity with higher dislocation density, because of the dislocation "cleaning up" the material in its immediate vicinity.⁸ However, because of the small separation of dislocations, the effects of an individual isolated dislocation are not directly seen.

Some work has also been done using scanning PL to map LEC In-alloyed GaAs substrates.^{6,7,10-12} The dislocation separation in In-alloyed GaAs is much larger than that in GaAs, so that the effects of individual dislocations can be observed. The work of Hunter *et al.*⁶ shows directly the effect of a dislocation on the luminescence in the surrounding region. This work correlated CL maps with dislocation positions, which were revealed directly by an etch pit density measurement. The results show that around a dislocation or cluster of dislocations there is an annulus in which the luminescence intensity is higher than the intensity inside or outside the annulus. Typically, the annulus has an inner diameter of 200 μm and an outer diameter of about 400 μm . A bright spot in the center of the inner dark region is seen for a cluster of dislocations but not for a single dislocation. Similar results are observed using photoluminescence. These annular features are larger than the dislocation separation in GaAs, so that they are not observed in GaAs. Attempts to measure the carrier lifetime show that in the bright region it is less than about 1.4 ns.¹¹ As seen in GaAs, the intensity of a 0.8-eV emission band associated with a trap anticorrelates with the dislocation density.¹¹ Thus, it has been suggested that this trap is involved in governing the lifetimes in the different regions.¹¹

It has been proposed that the pattern around a single dislocation is the result of one type of defect being gettered at the dislocation, producing the bright annulus, while at the same time, another type of defect is generated by the dislocation and diffuses away, giving rise to the dark region within the annulus.¹¹ (It is not clear what causes the bright spot at the center of the features caused by dislocation clusters.) The effects of dislocations in GaAs are expected to be similar. However, this will not be directly observable because the separation of the dislocations is too small for the effect of an individual dislocation to be seen.

The PL maps of both GaAs and In-alloyed GaAs substrates depend greatly on the thermal history of the substrates.^{8,10,13} For example, the PL for In-alloyed GaAs annealed for 30 min at about 800 °C with As loss reduced by a SiO₂ encapsulating layer becomes uniform and bright. Since it is known that defects diffuse during an anneal, this supports the view that the distribution of defects is responsible for the contrast.

In both of these substrates, surfaces are found to greatly affect the PL intensity. Photoluminescence intensities are found to vary with surface processing and with the dose of the exciting laser.^{8,14} These effects are thought to be due to surface capture. The effect of surface processing is to change

the surface recombination velocity. The variation with laser exposure time is thought to be due to the creation of surface defects by the laser beam itself.¹⁴

In this work, time- and space-resolved PL measurements are used to investigate the regions around a dislocation in In-alloyed GaAs to see if the carrier lifetimes correlate with the PL intensity variations. The time resolution is obtained using photoluminescence excitation correlation spectroscopy (PECS). PECS is a pump/probe correlation measurement described in detail in Ref. 15. It is well suited to the measurement of carrier lifetimes in samples in which the carrier lifetime is governed by capture onto traps.

For In-alloyed GaAs, surface capture can affect the PL intensity and the carrier lifetime. Using a recently proposed passivating layer,¹⁶ the effects of surface capture could be reduced dramatically. In this work, measurements for both passivated and unpassivated surfaces were made, so the importance of surface capture on the measurements could be deduced directly. When surface passivation affects the measurements the results described are for the passivated surface. Thus, the effects observed are not the result of surface capture.

Photoluminescence intensity maps of an as-grown In-alloyed GaAs wafer are made. Line scans of near band-to-band PL intensity are made across a bright annulus at 5, 77, and 300 K. Using PECS, lifetimes are measured at bright and dark positions at these temperatures. The lifetimes are found to vary as the PL intensity varies, with longer lifetime corresponding to greater PL intensity. For example, at 77 K, an intensity contrast ratio of 6.0 ± 0.5 is seen, with a lifetime ratio of 3.6 ± 1.0 , corresponding to lifetimes of 850 ± 20 ps in the bright region and 240 ± 10 ps in the dark region. Thus, the PL intensity is correlated with the difference in carrier lifetime. Further, the temperature dependencies of the carrier lifetimes in the bright and dark regions are very different. Thus, the dominating defects, which govern the lifetimes in the different regions, must be different. (They are not the same defects with different concentrations.) This result supports the suggestion, that one type of defect is gettered by the dislocation, while at the same time another type of defect is generated by the dislocation. The defects in both regimes have a deep electronic level rather than a shallow one because the lifetime does not increase at 300 K, contrary to expectations for a shallow level. Furthermore, neither type of defect is EL2, an important defect in these materials, because the lifetimes associated with EL2 at the concentrations in this sample are in the range of nanoseconds to microseconds, rather than hundreds of picoseconds.

II. EXPERIMENT

A. Apparatus

The PECS apparatus is discussed in detail in Ref. 15. A colliding pulse mode-locked (CPM) ring dye laser is used to generate pulses of 200 fs full width at half maximum (FWHM) with a repetition rate of 120 MHz. The pulse wavelength is centered near 6200 Å with a spectral width of about 20 Å FWHM. A single beam is separated into two pulse trains using an interferometer which allows the pulse

trains to be delayed with respect to each other by a variable delay time γ , and separately chopped at frequencies $f_1 = 1603$ Hz and $f_2 = 2005$ Hz. The two trains are recombined and focused down to a $25\text{-}\mu\text{m}$ -diam spot on the sample. Typically, the laser pump power was 1–2 mW per unchopped beam at the sample, or 8–16 pJ per pulse. The PL from the sample is spectrally resolved using a double-pass spectrometer and detected using a GaAs photomultiplier tube (PMT). The PMT signal is amplified and detected using a lock-in amplifier tuned to either the fundamental frequency f_1 or the difference frequency $f_{\text{diff}} = f_2 - f_1$. Spatial resolution is achieved using computer controlled translation stages to move the cold finger Dewar holding the sample. This is a particularly simple approach since the optics remain stationary, and the sample is translated in the plane normal to the incident beam. The resolution limit of scans is the $25\text{-}\mu\text{m}$ laser spot size. The cold finger Dewar is run with liquid helium, liquid nitrogen, and empty to achieve temperatures estimated to be about 5, 77, and 300 K, respectively.

B. Samples and processing

The samples are (100) In-alloyed GaAs with an InAs mole fraction of about 0.3%. The mapping studies were done using as-grown material. Electrical measurements on this material indicate an EL2 concentration of about $2 \times 10^{16} \text{ cm}^{-2}$, which compensates a C acceptor concentration of about $3 \times 10^{15} \text{ cm}^{-2}$. The concentration of donors is $< 1 \times 10^{15} \text{ cm}^{-2}$. For more details on the samples, see Ref. 6. The absorption depth of the radiation used is $0.25 \text{ }\mu\text{m}$, so that for the pump powers used, the excited carrier density is about 10^{17} cm^{-3} . A recently reported passivation scheme is used to reduce the effect of surface capture.¹⁶ It consists of spinning on a 0.5–1.0M aqueous solution of $\text{Na}_2\text{S} \cdot 9\text{H}_2\text{O}$, after a mild etch ($1:8:500 \text{ H}_2\text{SO}_4:\text{H}_2\text{O}_2:\text{H}_2\text{O}$) is used to strip off any native oxide, resulting in a colorless crystalline film. The effect of this film is stable for about a day. Because the film is water soluble, it can be easily stripped off, the sample re-etched, and a new passivation layer applied. In all the work done here, the passivation layer was less than a day old.

C. Procedure

The mapping experiments done in this work require the same part of the sample to be reanalyzed after the sample is taken out of the Dewar and processed. This was achieved by scribing a dot on the sample, which could be aligned with an accuracy of about $50 \text{ }\mu\text{m}$. The spectra are made using the PL signal at the fundamental frequency, and the delay-time scans are made by varying the delay time γ while monitoring the near band-to-band PL signal at the difference frequency.

III. RESULTS

The PL intensity and the carrier lifetime measured using PECS are found to be affected by the surface preparation.¹⁷ In addition, the PL intensity and the carrier lifetime measured using PECS are found to irreversibly change with laser exposure because of surface defects introduced by the laser.

These variations are most prominent at 300 K. Both of these effects are found to be due to the capture of carriers at surface defects. The effects of the surface defects are reduced dramatically by using the sodium sulfide etch. In this work, measurements for both passivated and unpassivated surfaces were made, so the importance of surface passivation on the measurements were investigated directly. Much attention was paid to reducing the amount of time the laser was on the sample during a measurement.

Figure 1 shows a low-resolution PL map along with a high-resolution map of the region outlined in the low-resolution map. These maps were made at 77 K for the intensity of the near band-to-band PL at $8280 \text{ }\text{\AA}$. The low-resolution map uses a $100\text{-}\mu\text{m}$ step and about 2 s per pixel, while the high-resolution map uses a $25\text{-}\mu\text{m}$ step and about 2 s per pixel. The three white lines marked on the high-resolution map and labeled A, B, and C, show the lines used to make line scans at 5, 77, and 300 K, respectively. These three different adjacent lines were used to eliminate laser dose effects. From the map at 77 K, the peaks and minima along these three adjacent lines are within 10% of one another so that features in the different line scans can be compared directly. The features shown in the high-resolution plot are very similar to those seen in Ref. 6. There are dark circular regions with or without a bright spot inside, corresponding to dislocation clusters and single dislocations, respectively. Surrounding these dark regions are bright annuli which have joined together.

Figure 2 shows the line scans made at temperatures of 5, 77, and 300 K along the lines A, B, and C for the passivated

FIG. 1. Photoluminescence intensity maps of the sample at 77 K. The top map is a low-resolution (0.1-mm step size) map of a large region, while the bottom map is a high-resolution (0.025 mm) map of the region outlined in the box in the upper map. PL intensity was monitored at $8280 \text{ }\text{\AA}$. Lines A, B, and C on the bottom map show the positions of line scans at sample temperatures of 5, 77, and 300 K.

FIG. 2. Photoluminescence line scans on sample. Line scans of photoluminescence intensity are plotted for the lines shown in Fig. 1. The graphs are for temperatures of 5, 77, and 300 K as marked. Solid curves are for unpassivated surfaces. Dotted curves are for passivated surfaces. The symbols —, O, and + mark the positions of the left-hand dark, bright, and right-hand dark regions, respectively.

and unpassivated surfaces. Comparing the passivated to unpassivated line scans, at 5 and 77 K very little difference is observed, while at 300 K a noticeable difference is observed. The contrast ratio at 5 K is about 20:1, at 77 K it is about 8:1, and at 300 K for the passivated case the contrast ratio is 4:1, while for the unpassivated case the contrast ratio is 2:1. On the y -position axes of Fig. 2 the bright region, and left- and right-hand dark regions are marked with O, +, and —, respectively. These mark the regions used to make spectra and delay-time scans considered typical of these areas. From Fig. 1 it appears that the left- and right-hand regions in all scans correspond to a dark area that is in close proximity to a dislocation.

Figure 3 shows the spectra made at the fundamental frequency of the bright and dark positions at 5, 77, and 300 K. The spectra at 300 and 77 K are for a passivated surface, and the spectra at 5 K are for an unpassivated surface. The spectra at 77 and 300 K show the near band-to-band peak. The shapes of the respective bright and dark spectra are the same, except that sizes are different. The spectra at 5 K show the near band-to-band peak and the acceptor related peak which are described more fully in Ref. 15. The near band-to-band peak does not change appreciably in shape for the spectra from the bright and dark regions; only the size is different. However, there is a large difference in the size of the

FIG. 3. Photoluminescence spectra of bright and dark areas. Spectra are at the fundamental frequency, at 5, 77, and 300 K. Solid curves are for the bright region, dashed curves are for the left-hand dark region, and dashed-dotted curves are for the right-hand dark region, corresponding to the positions marked O, —, and +, respectively, on Fig. 2. The spectra from the dark regions were scaled as shown. The spectra at 5 K were for an unpassivated surface, while the 77- and 300-K spectra were for passivated surfaces.

acceptor-related peak relative to the near band-to-band peak in the two positions. In the bright region, the acceptor-related peak is about 20% the size of the near band-to-band peak, while in both dark regions the ratio is less than 5%.

Figure 4 shows semilogarithmic plots of the delay-time scans made at the difference frequency at the bright and dark positions at 5, 77, and 300 K, for the passivated surface. Similar delay-time scans were seen for the unpassivated surface at 5 and 77 K. However, the delay-time scans of the unpassivated surface at 300 K were not symmetrical about zero delay time, indicating that laser dose effects, in this case degradation, were taking place. For this reason, only the delay-time scans from the passivated surface were used to determine carrier lifetimes. The scans at 77 and 300 K show a coherence peak at $\gamma = 0$ and the symmetric exponential decay on either side (linear on a semilogarithmic plot). The coherence peak is due to the optical interference of the two exciting pulses when they directly overlap and is not of interest in this work.¹⁸ The scans at 5 K show peaks at $\gamma = 0$ much wider than the coherence peak, with a FWHM of about 100 ps. This is due to capture of carriers by the acceptors and is not of interest in this work.¹⁸ The carrier decay associated with the bulk traps is the decay after the fast decay. The carrier lifetimes are determined by fitting the two

FIG. 4. Delay-time scans of bright and dark areas. Scans are at the difference frequency, at 5, 77, and 300 K. Solid curves are for the bright region, dashed curves are for the left-hand dark region, and dashed-dotted curves are for the right-hand dark region, corresponding to the positions marked O, —, and +, respectively, on Fig. 2. The scans are scaled for convenient display. All scans are for passivated surfaces.

sides of the semilogarithmic plot, excluding the coherence peak or the acceptor capture peak at $\gamma = 0$, to a straight line. A single carrier lifetime is expected because the carrier density is thought to be much greater than the density of traps. This requires the carrier populations p and n to remain close to one another as they decay. Table I summarizes the data from these passivated scans. The PL intensity for the different regions is determined from the same fits of the delay-time scans as for the lifetime fits. Thus, this measure of the PL intensity does not include the effect of the coherence peak or the acceptor-related capture peak. The PL intensity for the bright and right-hand dark regions and the ratio of these, called the contrast ratio, along with the ratio of lifetimes between these two regions are shown in Table II.

TABLE I. Carrier lifetimes of bright and dark regions.

Sample temperature (K)	Lifetime (ps)		
	Bright region (O)	Left-hand dark region (—)	Right-hand dark region (+)
5	$2100 \pm \frac{2000}{700}$	340 ± 60	260 ± 20
77	850 ± 30	230 ± 15	230 ± 20
300	580 ± 30	220 ± 60	220 ± 20

TABLE II. Photoluminescence intensity contrast ratio. The dark region with the best data was used. Values are from delay-time scans (difference) and from line scans (fundamental), along with the corresponding lifetime ratio. Results are for the passivated surface.

Sample temperature (K)	Intensity contrast ratio		
	Difference	Fundamental	Lifetime ratio
5	7.5 ± 2.0	17.5	$8.0 \pm \frac{9.0}{3.0}$
77	6.0 ± 0.4	5.6	3.7 ± 0.5
300	4.3 ± 1.0	5.0	2.6 ± 0.3

IV. DISCUSSION AND CONCLUSIONS

What is the effect of carrier diffusion on PL measurements? Using an ambipolar diffusion constant of $125 \text{ cm}^2/\text{s}$ at 77 K (Ref. 19) for a carrier lifetime in the range of 500 ps the associated diffusion of carriers over distances larger than $2 \mu\text{m}$. Comparing this to the $25\text{-}\mu\text{m}$ laser spot, it is clear that lateral diffusion is not important. Although this diffusion length is large enough to allow the carriers to reach the surface, the fact that the contrast is seen both with and without the surface passivation layer for all temperatures directly indicates that surface capture is not important in this work. Thus, the PL intensity contrast observed is due to the average bulk properties of the substrate, which vary over the features observed.

In earlier work, Hunter¹² observed a PL contrast ratio of 600:1 at 10 K. This is much larger than the 17.5:1 or 7.5:1 ratio shown in Table II for the contrast ratio observed at a comparable temperature in the fundamental or difference spectra, respectively. The discrepancy is probably due to the differences in the two experiments. The earlier work used a 1-mW cw laser with energy just above the band gap of the substrate, while in this work a 1-mW pulsed laser with energy 0.5 eV above the band gap is used. The pulsed laser generates peak carrier concentrations much larger than the cw laser. Moreover, the pulsed laser generates a much higher-temperature electron-hole plasma than the cw laser.¹⁵ These differences are probably significant enough to account for the difference of a factor of 30 in the intensity contrast. The difference between the contrast ratio as determined by the fundamental and difference signals is observed at 5 K, but not at 77 or 300 K. From the analysis of Ref. 15, the difference and fundamental intensity ratio for zero delay time should be the same for capture-dominated PL. The discrepancy at 5 K possibly occurs because in the bright region where the lifetime is larger than 1 ns, the electron-hole recombination is not completely capture dominated. If this were the case, the difference ratio would be less than the fundamental ratio as is observed.

Figure 5 shows a plot of the lifetime ratio and difference frequency intensity ratio of the bright to the right-hand dark region at 5, 77, and 300 K. From Ref. 15, the difference signal is given by

$$I_{\text{lock}}(\omega_2 - \omega_1) \propto (g^2 \tau / t_{\text{rep}}) e^{-|\gamma|/\tau}, \quad (1)$$

where g is related to the pulse power, t_{rep} is the laser-pulse

FIG. 5. Intensity contrast ratios and lifetime ratios with temperature. Plot (a) shows intensity contrast ratios at 5, 77, and 300 K. Plot (b) shows lifetime ratios at 5, 77, and 300 K. Both are ratios for the bright area to the left-hand area.

repetition rate, γ is the delay time, and τ is the carrier lifetime common to electrons and holes. So the difference signal is proportional to the lifetime for $\gamma = 0$. Figure 5 shows that this is indeed the case, although the agreement is not perfect. Thus, the intensity contrast is simply due to the lifetime contrast and is in agreement with earlier work for GaAs.⁹

At 5 K, the ratio of the carbon acceptor-related peak to the near band-to-band peak is found to vary strongly with position in the neighborhood of the dislocation. In the dark area the ratio is less than 5%, while in the bright region the ratio is about 20%. This could be a consequence of the acceptor concentration changing near the dislocation; however, this is not likely since earlier cw PL measurements do not show this effect.¹² The difference is more likely a consequence of the large difference in lifetime in the bright and dark regions. This lifetime difference in combination with the carrier temperature effects could give rise to such a difference in peak ratios. Thus, the variation in the carbon peak is probably a consequence of the large lifetime variation, not the other way around.

Figure 6 shows a plot of the lifetimes given in Table I with temperature. The temperature axis should be treated with caution because the actual temperature of the carriers producing the PL is substantially higher than the substrate temperature used in the plot, and varies in time, as discussed in Ref. 15. Thus, the temperatures plotted are only suggestive of the carrier temperatures involved. It is clear from Fig. 6 that both right- and left-hand dark areas have the same temperature dependence, and both of these are very different from that of the bright region.

Much information can be inferred from the lifetime behavior with temperature. The lifetime of either carrier that is due to one type of bulk trap is given by

$$\tau = (v_{th} N_t^* \sigma_t)^{-1}, \quad (2)$$

where v_{th} is the average carrier thermal velocity, σ_t is the

FIG. 6. Carrier lifetimes from bright and dark areas with temperature. Carrier lifetimes from bright areas, left- and right-hand dark areas are marked O, —, and +, respectively. The temperature axes only serves to display the points for sample temperatures of 5, 77, and 300 K.

trapping cross section, and N_t^* is the density of the trap level in the state to capture the carrier being considered. Using $v_{th} \propto \sqrt{kT}$, where T is the temperature of the carriers and $N_t^* \propto N_t$, where N_t is the total density of the trap, Eq. (2) becomes

$$\tau \propto [\sqrt{T} N_t \sigma_t(T)]^{-1},$$

where the temperature variation of the trapping cross section is explicitly shown. The change in τ with position is due to the variation in N_t for the dominant trap with position. However, in the case of the bright and dark regions, the different temperature behavior cannot be explained simply by a variation in N_t . Instead, there must be different traps dominant in the bright and dark regions. Thus, the same type of defect is dominant in the two dark areas, while a different type of defect is dominant in the bright area. For both dark areas to be similar indicates that both the dark areas are due to the proximity of dislocations, as the high-resolution map in Fig. 1 suggests. The fact that the dark and bright areas are due to different defects supports the model proposed by Hunter,¹¹ that the lifetime killer responsible for the dark areas away from the dislocation is gettered in the neighborhood of the dislocation, while another type of defect is generated by the dislocation. This model gives rise to a bright region because of the reduction of the population of one type of defect and to the central dark region because of the increased population of the generated defects. Models for the gettering and emission of defects at dislocations have also been proposed by Weber *et al.*²⁰

It is a difficult problem to determine the identity of the defects involved; however, they can be characterized to some extent. First, neither defect is shallow since a shallow defect at higher temperatures would ionize and reduce its effectiveness as a trap causing an increase in the carrier lifetime which is not observed. Second, neither defect is EL2, the defect responsible for the pinning of the Fermi level near

midgap in this material. This is because the capture cross sections for holes and electrons on EL2 predict carrier lifetimes much larger than those measured. From Ref. 21 the capture cross section of holes on EL2 is $1 \times 10^{-18} \text{ cm}^2$ at 77 K ($1 \times 10^{-18} \text{ cm}^2$ at 300 K) and for electrons on EL2 is $6 \times 10^{-18} \text{ cm}^2$ at 77 K ($4 \times 10^{-16} \text{ cm}^2$ at 300 K). Taking the concentration of EL2, $2 \times 10^{16} \text{ cm}^{-3}$ as the concentration of either the neutral EL2 which captures holes or the charged EL2 which captures electrons gives a lower limit of the hole lifetimes as $3.6 \mu\text{s}$ at 77 K ($1.5 \mu\text{s}$ at 300 K) and a lower limit of the electron lifetime as $0.36 \mu\text{s}$ at 77 K (2.6 ns at 300 K). These lifetimes are orders of magnitude larger than the measured lifetimes both at 77 and 300 K. Finally, from Eq. (2) a measurement of lifetime of about 500 ps, and a thermal velocity of 10^7 cm/s (typical for 300 K), give a value of $N_t \sigma$, of about 200 cm^{-1} . If either of the dominant defects is electrically active, then N_t must be in the range of 10^{15} cm^{-3} ; otherwise, they would dominate the electrical properties, which is not observed to be the case.¹¹ This condition on the density of defects requires the defects to have a cross section greater than $2 \times 10^{-13} \text{ cm}^2$, which is very large. If the defect is not electrically active, then the trap density could be larger so that the cross section need not be as high. From these measurements, it is not possible to tell whether or not the defect is electronically active.

The practical interest of the work is the effect these defects have on devices. Clearly the nonuniform nature of the PL intensity indicates that the as-grown material is not at equilibrium. This is confirmed by the result that annealing the material causes the PL intensity to become more uniform and bright. Thus, it is not surprising that the effect of the dislocations of the final devices is very dependent on the processing used.

V. SUMMARY

In this paper, the first space- and time-resolved PL measurements of the region associated with a single dislocation in a SI LEC In-alloyed GaAs substrate are described and discussed. The advantage of In-alloyed GaAs over GaAs substrates for such measurements is that the much larger dislocation separation in the alloyed material reduces the overlap of the effects of dislocations. In the alloyed material, the effects seen can be associated with the effects of a single dislocation. The time resolution is obtained using PECS and allows the measurement of the carrier lifetimes. The PL maps show the PL intensity variation in the neighborhood of dislocations. These maps show the same bright annular feature surrounding a dark central region at the dislocation, seen elsewhere.⁶ Measurements of the PL intensity over a line scan for different temperatures with and without a surface passivation layer show that the intensity contrast is not due to surface capture. Lifetime measurements at various positions along these line scans show that the intensity variations are caused by carrier lifetime variations. Carrier lifetimes in the dark regions were in the range of 220–340 ps,

while in the bright region, 580–2100 ps. The temperature behavior of these measurements indicates that these variations in lifetime are due not simply to the variations in the defect density of a single dominant trap. Instead, they are due to two different dominating traps, one in the bright annular region, and another in the dark regions near the dislocation, supporting the model proposed by Hunter,¹¹ that one type of defect is generated by the dislocation, while another type of defect is generated by the dislocation. From the lifetimes and their temperature behavior, neither type of defect is shallow, nor are they directly due to capture onto EL2.

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- ¹S. Miyazawa, Y. Ishii, S. Ishida, and Y. Nanishi, *Appl. Phys. Lett.* **43**, 853 (1983).
- ²H. V. Winston, A. T. Hunter, H. M. Olsen, R. P. Bryan, and R. E. Lee, *Appl. Phys. Lett.* **45**, 447 (1984).
- ³F. Hyuga, K. Watanabe, J. Osaka, and K. Hoshikawa, *Appl. Phys. Lett.* **48**, 1742 (1986).
- ⁴T. Egawa, Y. Sano, H. Nakamura, and K. Kaminishi, *Jpn. J. Appl. Phys.* **25**, L973 (1986).
- ⁵M. van Hove, W. de Raedt, M. de Potter, M. van Rossum, and J. L. Weyher, in *Materials Research Society Symposium Proceedings* (Materials Research Society, Pittsburgh, PA, 1988), Vol. 104.
- ⁶A. T. Hunter, H. Kimura, H. M. Olsen, and H. V. Winston, *J. Electron. Mater.* **15**, 215 (1986).
- ⁷D. Guidotti, H. J. Hovel, M. Albert, and J. Becker, in *Review of Progress in Quantitative Nondestructive Evaluation*, edited by D. O. Thompson and D. E. Chimenti (Plenum, New York, 1987), Vol. 6B, p. 1369.
- ⁸H. J. Hovel and D. Guidotti, *IEEE Trans. Electron Devices* **ED-32**, 2331 (1985).
- ⁹K. Leo, W. W. Rühle, and N. M. Haegel, *J. Appl. Phys.* **62**, 3055 (1987).
- ¹⁰H. J. Hovel, M. Albert, E. Farrell, D. Guidotti, and J. Becker, in *Semiconducting III-V Materials* (Ohmsha, Tokyo, 1986), p. 97.
- ¹¹A. T. Hunter, *Defect and Diffusion Data* **48**, 1 (1986).
- ¹²A. T. Hunter, *Appl. Phys. Lett.* **47**, 715 (1985).
- ¹³N. M. Haegel, A. Winnaker, K. Leo, W. W. Rühle, and S. Gisdakis, *J. Appl. Phys.* **62**, 2946 (1987).
- ¹⁴D. Guidotti, E. Hasan, H. J. Hovel, and M. Albert, *Appl. Phys. Lett.* **50**, 912 (1987).
- ¹⁵M. B. Johnson, T. C. McGill, and A. T. Hunter, *J. Appl. Phys.* **63**, 2077 (1988).
- ¹⁶C. J. Sandroff, R. N. Nottenburg, J.-C. Bischoff, and R. Bhat, *Appl. Phys. Lett.* **51**, 33 (1987).
- ¹⁷M. B. Johnson and T. C. McGill (unpublished).
- ¹⁸M. B. Johnson, Ph.D. thesis, California Institute of Technology, 1989.
- ¹⁹Calculated using ambipolar diffusion constant $D_a = 2D_n D_p / (D_n + D_p)$, using $D_n = 1300 \text{ cm}^2/\text{s}$ and $D_p = 66 \text{ cm}^2/\text{s}$. See S. M. Sze, in *Physics of Semiconductor Devices* (Wiley, New York, 1969), p. 99.
- ²⁰E. R. Weber, H. Ennen, U. Kaufman, J. Windscheif, J. Schneider, and T. Wosinski, *J. Appl. Phys.* **53**, 6140 (1982).
- ²¹V. Ya. Prinz and S. N. Renchukhov, *Phys. Status Solidi B* **118**, 159 (1983).