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LOW VOLTAGE SCANNING ELECTRON MICROSCOPY CATHODOLUMINESCENCE OBSERVATIONS OF GALLIUM ARSENIDE

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Abstract

A series of low voltage (< 5 keV) and low temperature (< 20K) cathodoluminescence (CL) measurements were performed on epitaxial gallium arsenide. The purpose of these measurements was to ascertain which factors were important in furthering the development of low voltage scanning electron microscopy (LVSEM) CL. LVSEM CL potentially offers great improvement in spatial resolution and the ability to probe the optical properties of surface states. Anomalous CL effects resulting from contamination at beam voltages below 3.5 keV have been interpreted in terms of cross-over potential phenomena. Luminescence dead layers were reduced to near zero in this regime. Excitonic processes were found to be particularly sensitive to injection level and surface conditions. Very weak free-to-bound transitions persisted down to 200 eV beam voltage.

Key Words: Low Voltage Scanning Electron Microscopy, Cathodoluminescence, Gallium Arsenide, Luminescence Dead Layers, Contamination, Cross-Over Voltage.

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Introduction

The use of low energy electrons (beam voltages < 5 keV) has yielded many applications in scanning electron microscopy. Examples include; the imaging of passivated microcircuits through charge control, and improving the spatial resolution of X-ray microanalysis through reduced beam spreading effects. In this article, we are concerned with cathodoluminescence (CL) applications. A number of publications have already appeared on this subject in the literature. Brillson and Viturro (1988) have performed low energy CL spectroscopy of InP and CdS in an ultra-high vacuum (UHV) based electron beam apparatus. Their results revealed changes in CL spectral features at room temperature which were correlated with changes in the electronic structure of the surface as a result of metallization, laser annealing, and thermal desorption. This work demonstrated that the depth tunability available with beam voltage control can be used to differentiate the sub-surface region of a semiconductor from the bulk. A more recent application demonstrated that low voltage SEM CL (1 keV) of quantum structured III-V devices can offer superior spatial resolution (600 Å) (Warwick, unpublished). This improvement was achieved by utilizing the deleterious recombination properties at the semiconductor surface in order to limit carrier diffusion. A similar effect was reported by Cumberbatch et al. (1981) in CL imaging experiments of silicon at higher voltages (30 keV). In the former case, the surface acts as a pico-second 'shutter' where for times greater than ~ 10 ps, non-radiative recombination dominates. This phenomenon in conjunction with the reduced electron scattering at lower beam voltages promises further improvements in resolution. A better understanding of the factors which may limit progress in this matter and LVSEM CL in general is clearly important. For example, the role of surface recombination velocity, the properties of luminescence dead layers, cross-over voltage phenomena and contamination are all relevant to such studies. We report on progress in addressing some of these questions.

Experimental

The measurements reported here were performed in a turbomolecular pumped JEOL 840 SEM equipped with a W-filament. The low temperature, spectral CL apparatus used in these experiments was designed around an Oxford Instruments CL301H cold stage. The system was equipped with single photon counting detection. The samples used were nominally undoped n-type GaAs epitaxial layers

grown by organo-metallic chemical vapour deposition on semi-insulating GaAs substrates: the carrier concentration was ≈ 1.5 x 10^{14} cm^{-3}, μ_{77K} ≈ 115,000 $cm^2/V/s$, and the epilayer thickness was ≈ 9 µm. Such specimens were chosen in order to optimize spectral quality and sensitivity. The samples were ultra-sonically degreased in trichloroethane, acetone and propanol prior to loading into the SEM. In addition, it should be noted that the samples had been air aged in the laboratory over a period of months: the oxide thickness was typically 25 Å. The samples were allowed to outgas in the regular SEM vacuum for at least 12 hours prior to any experimentation. This procedure results in some consolidation of the oxide layer through water loss. The SEM vacuum was typically 3 x 10^{-7} torr under cryo-pumping conditions. In this LVSEM CL investigation we have restricted the study to the behaviour of the band edge luminescence properties.

Results

To begin with, it would be useful to establish, given the non-uniform nature of electron beam excitation, how CL generation varies with beam voltage . Intuitively, one would expect factors such as, surface recombination velocity and luminescence dead layers to be more prominent at lower voltages. In Figure 1 we show a typical low temperature (20K) integrated CL depth profile (CL intensity versus beam voltage).

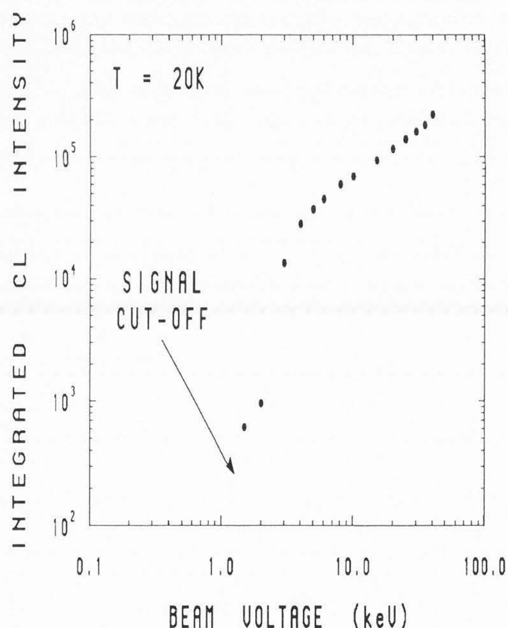

Figure 1: A CL depth profile: Integrated CL intensity versus electron beam voltage at 20K (band pass, 5 Å).

The data was acquired under the following conditions: an area (3000 μm^2) of the sample was rastered at reduced TV rates (30 Hz) under constant incident beam power (1 µW). This relatively low beam power ensured a linear CL response with excitation. In other words, no 'bottlenecking' or saturation of any of the near band edge radiative transitions was observed with the above excitation conditions. Indications of 'bottlenecking' would be evident from shifts and broadening of the donor-acceptor pair transition and electron heating of the free-to-bound carbon acceptor transition. This low power also minimized anomalous contamination effects which will be described in more detail later.

The experimentally determined CL signal cut-off voltage (1.2 - 1.5 keV from Figure 1) did not actually have a precise value since it primarily reflected the prevailing carrier recombination kinetics and overall system detectivity. The CL signal cut-off was found to be strongly dependent on the excitation conditions (specifically, the incident beam current). The different radiative transitions observed in GaAs at these low temperatures also exhibited different dependencies on excitation. For example, in Figure 2 we show a CL excitation series performed at 1.5 keV (very close to the cut-off voltage). At the lowest power (1 µW) the CL emission spectrum was characterized by very weak free-to-bound acceptor transitions $(e,A^o)_C$ (we were not able to detect excitonic processes). However, excitons were observed at the higher injection powers (3 - 5 µW). Note that the integrated CL output (summation of all of the near band edge transitions) was directly proportional to the beam current for this excitation series (i.e. linear dependence). It is also worth noting that a similar injection dependent effect was observed at higher beam voltages.

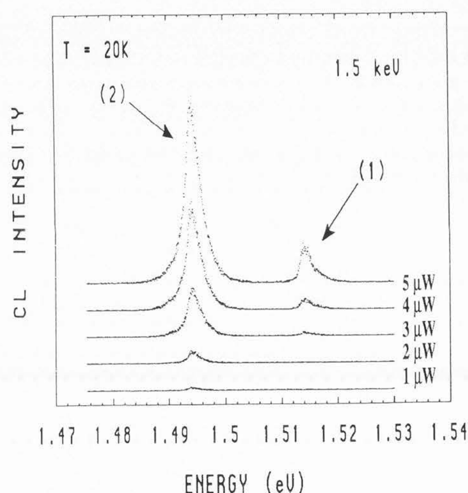

Figure 2: Spectral CL power excitation series at 1.5 keV. Region (1) corresponds to excitonic transitions, and region (2) corresponds to free-bound transitions. Note, spectra have been shifted vertically for clarity.

See Figures 3 (a) and (b) (beam power = 50 nW and 1 µW, respectively) which shows higher resolution (band pass, 2 Å) CL spectra acquired at 25 keV with the probe in spot mode. The samples used here had prior extensive photoluminescence characterization performed in order to identify the radiative transitions (Davito et al. 1990). At the lower power (50 nW) the spectra was dominated by non-excitonic processes: free-to-bound carbon acceptor $(e,A^o)_C$, and donor-acceptor pairs $(D,A)_C$, and $(D,A)_{Zn}$. Again, the excitonic processes were observed only at the higher power (1 µW): free excitons (FE, n=1, n=2), neutral donor bound excitons (D^o,X), ionized donor bound excitons (D^+,X) (with probable contributions from donor-

valence band transitions D^o,h), and neutral acceptor bound excitons (A^o,X). These observations clearly demonstrate the CL injection sensitivity of nominally undoped GaAs at low temperatures.

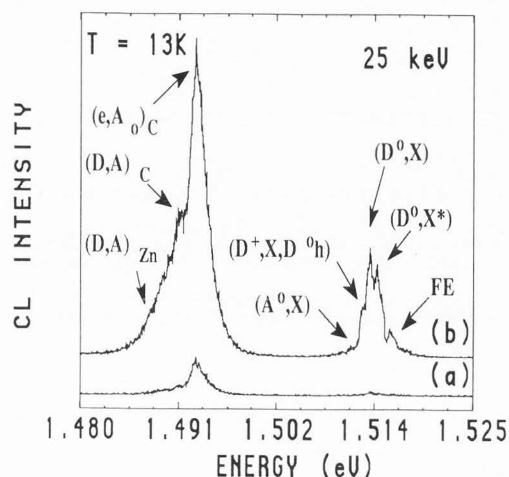

Figure 3: Spectral CL excitation comparison at 25 keV (band pass, 2 Å), (a) beam power = 50 nW and (b) beam power = 1 μW. Note, spectra have been offset for clarity.

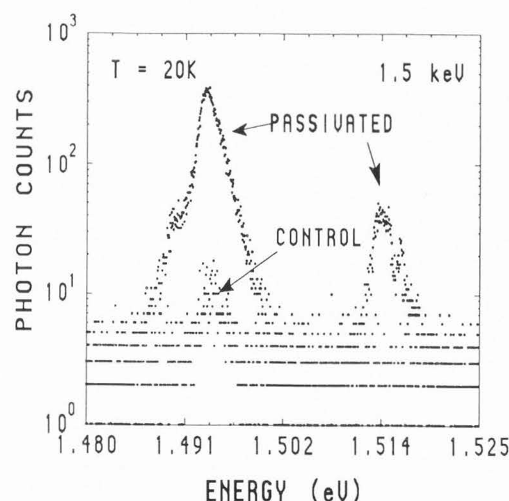

Figure 4: Log-linear plot of CL spectra recorded before (control) and after contamination (passivation) at 1.5 keV with 1 μW beam power (band pass, 5 Å).

Earlier we alluded to low voltage-low temperature contamination phenomena which necessitated the use of relatively low beam powers in the experiments described above. It was observed that prolonged exposure (typically > 10 minutes) of the sample to beam powers in excess ~ 7.5 μW resulted in the formation of a 'contamination' layer. The specific kinetics of this process were not investigated in this study, except, it was noted that the phenomenon was dosage dependent. Typically, the dosage required in order to generate the contamination phenomenon in these samples was found to be 0.06 - 0.2 C/cm^2 at 1.5 keV. In itself these results are not new, since contamination has been an inherent part of electron microscopy from the earliest observations. However, what made this particular contamination phenomenon interesting was the subsequent 'passivation' effect on the low voltage CL properties of GaAs.

In Figure 4, we show CL spectra before (control) and after contamination (passivation) recorded at 1.5 keV under the same low power excitation conditions as described earlier in Figure 1. Excitonic features not present before were clearly observed following contamination. Corresponding (e,A^o) peak intensity gains were found to vary between x50 - x500 following contamination.

This passivation effect thereby enabled CL measurements to be performed below the previously defined cut-off voltage. In Figure 5 (a) we show a spectrally resolved CL image (n=1 FE transition) of the 'passivated' area recorded at 1.2 keV, (b) the corresponding secondary electron image (SEI), and (c) a numerically manipulated superimposed image of the SEI and CL image. This latter image shows a 'bright' CL rim corresponding to the dark SEI contrast associated with the perimeter region of the contamination. The contamination film was found to have a 'permanent' effect on the CL. Specifically, when the sample was viewed subsequently by panchromatic CL at room temperature the area was dark. In this sense, it was a typical example of SEM contamination: resulting in reduced CL emission, as opposed to the anomalous low temperature results.

Once the sample had undergone the low temperature-low voltage contamination, CL depth profile measurements were possible all the way down to 200 eV under the same low excitation conditions as used for the acquisition of the data in Figure 1. Figure 6 summarizes these measurements in a normalized format (CL intensity versus beam voltage): we include the original Figure 1 profile for reference, and show the effect of contamination (see arrow indication), and the measurements performed in reverse from 2 keV back to higher voltages (up to 40 keV). A CL cross-over was observed at ~ 3.5 keV, that is, the beam voltage above which the contaminated area of GaAs appeared darker than the surrounding material.

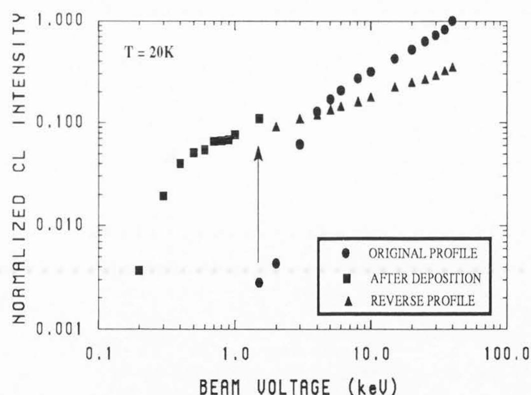

Figure 6: A combination CL depth profile: Normalized (integrated) CL intensity versus electron beam voltage before and after contamination. The data has been normalized relative to the original CL intensity at 40 keV. (Circle - represents original data as per Fig.1, Square - CL profile following deposition of contamination, Triangle - reverse CL profile).

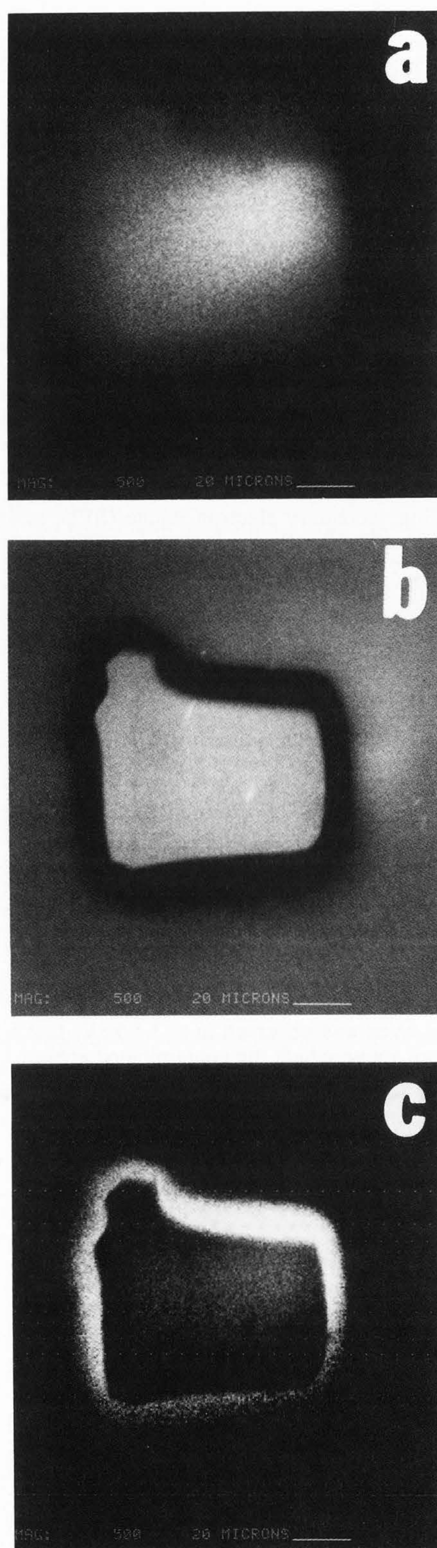

Figure 5: Photographs of (a) excitonic CL image of contaminated area, (b) secondary electron image of the same area, and (c) a combination image of (a) and (b).

Discussion

This preliminary investigation of LVSEM CL has raised several important questions. A key factor in these observations unfortunately revolves around the nature of the contamination. Contamination effects are known to be a complex function of beam voltage, surface charge, and specimen temperature. For example, etching of the specimen can take place at low temperature (< 173K) where carbonaceous films can be reactively removed by adsorbed water vapour: see the extensive review by Hren (1986). We do not attempt to address the contamination process in any detail here, but rather discuss in a phenomenological context, its effects on CL. The occurence of dark raster squares is not unusual in CL. In low doped semiconductor material the surface charge can result in a deeper depletion region which causes enhanced carrier transport to the surface where non-radiative recombination dominates. Conversely, if surface repulsion of carriers occurs, white raster squares may be observed (Warwick, 1987). We discuss these effects in more detail.

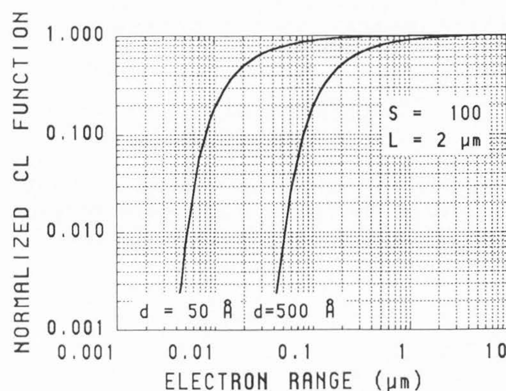

Figure 7: Theoretical CL depth profile as a function of dead layer thickness (d).

To begin with we will consider the CL dependence on beam voltage The basic shape of CL profile in Figures 1 and 6 can be understood by the phenomenological model developed by Wittry and Kyser (1967). In Figure 7 we show normalized CL depth profiles (CL intensity versus electron range) derived from this model. In particular, we demonstrate the effect of dead layer thickness variation on CL output. In this plot, we have used the Gaussian approximation suggested by Orton and Blood (1990) for the carrier generation profile and the electron range calculation recommended by Joy and Luo (1989). Note, CL self-absorption and electron backscatter variation with voltage were not taken into account in the generation of Figure 7. The following parameters are defined: S is the reduced surface recombination velocity (surface recombination velocity divided by diffusion velocity) L is the carrier diffusion length and d is the luminescence dead layer thickness. The values of S = 100 and L = 2 μm were chosen to reflect high surface recombination activity and ambipolar diffusion for the given epilayer. It is evident that the 'signal' cut-off point is strongly dependent upon the dead layer thickness (all other things being equal). The physical basis for the dead layer is normally attributed to the surface depletion region: this is where spatial separation of the generated electron-hole pairs can take place.

In a photoluminescence study of InP by Hollingsworth and Sites (1982), it was demonstrated that a functional dependence existed between the dead layer thickness and the depletion width. The dead layer thickness could be controlled with bias, and it was found to be consistently less than the depletion width by about 500 Å. This result implies that the dead layer can be reduced to effectively zero without necessarily requiring flat band conditions. In the samples used here the 'dark' (electron beam off) surface depletion width was expected to be 2 - 3 μm. The injection of electron-hole pairs will act to reduce the band bending (ϕ), and hence the surface field, provided the surface states are capable of charge exchange with the bands. We demonstrate this schematically in Figure 8 (a) and (b) which shows band energy and electric field (E) as a function of depth (x), respectively. The change in depletion width Δd under electron beam excitation will result in a corresponding reduction in the dead layer thickness. The presence of residual surface fields under electron beam excitation can explain the signal cut-off in

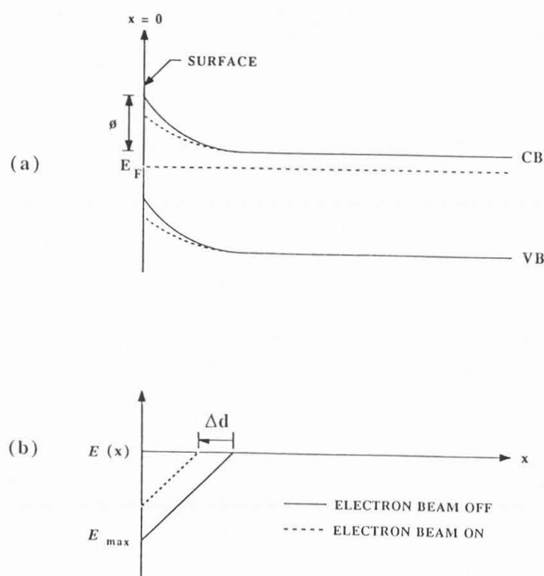

Figure 8: Schematic of (a) energy band and (b) electric field under electron beam excitation. This figure illustrates the reduction in depletion width (Δd) under excitation.

Figure 1 and the 'quenching' of excitonic processes at the lower voltages. Specifically, excitons are particularly sensitive to field ionization compared with free-to-bound transitions. The dip in the FE line in Figure 3 has been attributed to such a process close to the surface (Schultheis et al., 1987). Therefore, it would be expected that the cut-off voltage for exciton detection would be excitation dependent: the injection level would determine the residual field. Note, that an alternative interpretation for the FE resonance dip has been described in terms of exciton-polariton interactions (Hopfield, 1969). However, on the basis of the former argument, we feel the dramatic change in the CL properties with contamination primarily reflects a reduction in the dead layer thickness. Further, this change in the CL depth profile could not be accounted for (using Wittry's model) by any dramatic reduction in surface recombination velocity alone (even if S went to zero). Incidentally, the values of d (50 Å and 500 Å) were purposely selected for Figure 7 in order to provide a reasonable fit of the experimental data in Figure 6 (as far as the CL cut-off point was concerned).

The question now arises: What is the source of the additional 'bias' which further modulates the surface depletion region? It is interesting to note that cross-over phenomena occur at the low voltages used in these experiments. By cross-over we are now referring to secondary (σ) and backscattered (η) electron yield dependence on beam voltage. Two cross-over potentials, E_1 and E_2 are usually defined where $(\sigma + \eta) = 1$. For beam voltages $E_0 > E_2$, negative charging can result if sample conductivity is poor. For intermediate beam voltages, i.e. $E_1 < E_0 < E_2$ 'positive' charging may occur resulting in a surface potential of a few volts. In addition, contamination can act to modify the secondary yields, and hence, the potential distributions. We speculate that the 'contamination' in conjunction with the cross-over phenomenon generates an 'auto-bias' condition at the GaAs surface. Joy (1987) has calculated E_2 to be 2.6 keV for GaAs and 0.65 keV for carbon (the contamination product ?), and Brunner and Menzel (1983) have experimentally determined E_2 at room temperature to lie between 4.2 - 4.5 keV for various GaAs epilayers and < 1.1 keV for carbon. The anomalous CL behaviour was observed below these voltage values. The SE image of Figure 5 (b) adds further credibility to this idea: to begin with, the contamination square appears slightly brighter than background, suggesting a more 'negative' potential. However, directly underneath the film, the underlying GaAs appears to be at a more 'positive' potential than the nominally uncontaminated background material: this is suggested by the dark SEI contrast around the perimeter of the film. It is not unreasonble to assume that this contrast reflects the spatial extent of potential spreading (about 15 μm). The CL was correspondingly weaker in this transition region. See Figures 5 (a) and (c), again, for the comparison of signal strengths in the perimeter and directly underneath the film. Therefore, the contamination film, when subject to electron beam excitation, is acting like a Schottky contact on the GaAs: in which case a potential difference of less than a volt would be required to reduce the dead layer thickness to zero (Hollingsworth and Sites, 1982). This inference of a differential cross-over effect could explain the return of excitons.

As a final comment, the excitonic processes were again observed to quench with reducing beam voltages down to 200 eV (only free-to-bound transitions were observed). Other mechanisms must be invoked to account for this behaviour, for example, the exciton 'image force barrier' (Hopfield and Thomas, 1963). This force originates from the repulsive interaction of the exciton with its electrical image when the former approaches the surface. This distance would correspond closely to the effective Bohr diameter ~ 300 Å in GaAs. This would limit the sampling depth (or sample thickness for that matter) for exciton detection. We include this item in the discussion to highlight the complex nature of luminescence phenomena.

Conclusions

It is clear that many interesting phenomena can take place at low voltages and low temperatures, and that there is some interplay between the different interaction mechanisms. We have shown that low voltage SEM CL

phenomena are complex. In this work, we have attempted to link voltage cross-over phenomena with contamination and anomalous CL effects. More studies need to be conducted in order to establish the limiting factors in the development of LVSEM CL. For example, would the aforementioned observations occur in a UHV SEM equipped with a field emission gun. This would be relevant to 'contamination' effects from the current density-dosage point of view.

Acknowledgements

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Discussion with reviewers

D.B. Holt: What is meant by 'bottle-necking'?
Author: We use 'bottle-necking' as a general term to describe the situation when relaxing particles (electrons, excitons, polaritons, etc.) accumalate at some particular point on the energy-wavevector (E-k) curve. This bottle-necking will change the rate of subsequent radiative recombination. An example of bottlenecking occurs at the knee of the lower polariton branch of many semiconductors, where if the density of thermalized exciton-polaritons is high, annhilation into photons in the vacuum may be pre-empted by competion with other energy loss mechanisms (scattering, ionizaton, etc.). This can lead to non-radiative relaxation-recombination of the exciton-polaritons.

D.B. Holt: What is meant by normalized in Figure 6?
Author: The source of the CL data in Figure 6. is the summation of the 'photon counts' in the excitonic, donor-acceptor, and free-to-bound emission bands. This represents the integrated near band edge CL intensity for each voltage measurement. The data presented in the figure has been normalized to the 'original' integrated photon count measured at 40 keV. This was done to facilitate comparison with Figure 7: the CL profile due to Wittry's model.

D.B.Holt: You ascribe many interesting effects to 'contamination'. The fact that you put the word in inverted commas suggests that you are not entirely convinced about the mechanism. A reason for thinking that contamination by beam bombardment of pump oil on the surface is unlikely to be the cause is that the time required (typically > 10 minutes) and the low vacuum pressure attainable with turbo pumping would not result in build up of an appreciable field thickness. The obvious alternative explanation is 'damage' (also an ill-defined term). The effects you report are the result largely of surface charging. this could occur by a variety of mechanisms. Deep traps could hold charge for long times and reduce band bending, etc. The effect of gentle annealing might distinguish between charge trapping and carbon-film contamination.
Author: We answer this comment in two parts: Firstly, in additon to using a turbo-pump to minimize hydrocarbon contamination, we have used moly-disulphide as a dry lubricant for most of the internal moving mechanisms in the chamber (stage, etc.). However, since we do not have a foreline trap, oil from the backing pump does backstream into the specimen chamber. This fact is supported by the observation over a period of months of condensed oil on our cooled X-ray detector. Therefore, we do not completely eliminate pump oil as a source of contamination. Secondly, some kind of charging phenomenon does appear to be the likely explanation for the CL effects, since the CL 'gain' is observed to degrade with extended time (> 90 minutes) without beam bombardment, viz. slow discharge.

D.B. Holt: You also use the term 'passivation', at one point as equivalent to 'contamination', to describe the cause of observed changes in CL exciton emission and voltage cut-off. This too appears to be surface charging, rather than, necessarily, changes in surface states densities. Of course charge could be trapped in a carbon film (is there any evidence that this happens?) or by interface states under the film, but equally they could be trapped in already existing deep levels at or near the surface.

Author: We have found that in experiments with evaporated carbon films (50 - 100 Å), similar beam excitation dosages were required in order to produce the CL changes. This result may suggest that the charge trapped in the carbon (evaporated thin film form or 'contamination' form) may be responsible for the phenomenon. Work continues in this area.

D.B. Holt: You quote (e,A^o) peak intensity increases of x50 - x500. These values seem very large and appear to arise from comparison of values near the CL cut-off voltage. We have observed x4 increase in integral CL intensity from a quantum well structure after a minute of exposure. This change can be explained by a filling (saturation) of non-radiative recombination centres. Have you considered such mechanisms as the possible causes of your effects?
Author: The peak and integrated intensity gains are certainly more dramatic close to the CL cut-off voltage. From Fig.6 it can be seen that the integrated CL 'gain ratio' is a function of beam voltage. For example, the typical 'gain' at say 2 keV is x10 - x20. This 'gain' is also sensitive to excitation power viz. injection conditions. On the matter of saturation of non-radiative centres: the filling of, and subsequent charge storage in surface traps is another potential candidate to explain our effects at liquid helium temperatures. Especially since at the low beam voltages the excess carrieers will be effectively confined close to the surface. We have not explored this aspect in any detail. However, in terms of a time storage factor, we do know the effect persists for at least 1 hour following 'contamination' at low temperature without electron irradiation.

A. Jakubowicz: Your results are explained by a build-up of charge in the contamination layer. Have you observed any changes of the CL signal due to electron irradiation, indicative of a modification of the semiconductor's defect state in the near-surface region?
Author: We have not observed changes in CL spectral character which can be directly attributed to a modification of the surface states by electron bombardment. The general changes in spectral character which were observed we feel reflect primarily changes in the recombination kinetics associated with injection level differences. On a similar, but separate issue, we have observed changes in the exciton lineshape (absence of exciton resonance) with surface passivation (ammonium sulphide treatment) in the same epitaxial GaAs material. This may be related to changes in surface defect states.

A.Jakubowicz: Have you observed similar effects in other samples?
Author: Yes, we have observed similar effects with p-type GaAs epitaxial layers grown on semi-insulating substrates and n-type GaAs epitaxial layers grown on n^+ substrates. In addition, we have seen the effect on GaAs epixatial layers which have been subjected to ammonium sulphide passivation treatment and carbon coating. In the former case, the treatment is thought to produce a monolayer of As_xS_y on the GaAs surface which modifies the surface states density. The effect thus far appears to be insensitive to original surface condition, i.e. whether oxide coated, carbon coated, sulphide coated. This suggests that the low voltage CL effect is primarily related to a 'charging' phenomenon.

J.F. Bresse: Could you not explain the presence of the dead layer of contamination giving no cathodoluminescence emission? The emission starting at a beam energy of 1.5 keV corresponds to a penetration of electrons of around 50 nm, equal to the dead layer thickness. The effect of the electron irradiation should reduce the dead layer thickness by desorption of the species of the contamination layer.
Author: This is certainly possible since adsorption and desorption processes at low temperatures are complex. Especially since impurity adsorption and desorption can modify the work function, surface states, charging, etc. of a semiconductor, see for example, T. Wolkenstein (1991), Electronic processes on semiconductor surfaces during chemisorption (Plenum Publishings) p367 - 420. Such processes will then have a subsequent effect on the luminescence efficiency. However, in this particular case the 'process' would have to be voltage dependent in order to account for the reverse profile following deposition in Figure 6. The role that adsorption, desorption, etc. plays in the cathodoluminescence of semiconductors is an area for new interesting research.

J.F. Bresse: Have you done complementary experiments to determine the chemical nature of the contamination?
Author: No, we have not.

D.C. Joy: Goulding (1977, Nucl.Instrum. and Methods., 142, 213-223) and others have speculated that the 'dead layers' are essentially the result of competion between drift and diffusion. The dead layer width therefore depends on both the surface condition as well as on the temperature etc. Does their model shed any light on your observations?
Author: Goulding describes the loss of carriers by diffusion to the surface before their collection by the electric field in a X-ray silicon detector. The dead layer thickness is defined as where the carrier diffusion length and carrier scattering mean free path are set equal. Conceptually, if the carriers are able to 'diffuse' to the surface (and are lost there) before the effects of the electric field (drift) are felt, a dead layer for carrier collection can be imagined. In our experiments, the excess carriers generated within the surface depletion region will also be subject to drift and diffusion. The primary effect should be the separation of electrons and holes by the surface field. Some residual surface field will exist because of the relatively low excitation conditions used in these experiments. This separation of carriers should greatly reduce the probability of radiative recombination, especially for excitonic transitions. We have observed this experimentally, that as the beam voltage is decreased, excitonic transitions disappear more rapidily than free-to-bound or bound-to-bound transitions. However, it should be noted that geminate recombination is still possible, that is, where the carrriers are able to recombine radiatively before the effects of the field are felt. This is analogous to the effects described in Goulding's model. The separation of carriers by the surface field has provided the traditional basis for the luminescence dead layer. A scenario can then be imagined where the excess carriers that arrive at the edge of the depletion region are then able to diffuse into the neutral bulk and recombine radiatively at some later point in time. However, the depletion width is modulated to some extent by the carrier injection level. Specifically, the higher the concentration of excess carriers generated, the lower the band bending, and therefore, the surface field is reduced (assuming at least one of the quasi-Fermi levels can move). This should yield a corresponding decrease in the dead layer thickness. It was not possible in our experiments, because of the anomalous low voltage 'contamination', to directly observe reproducible effects on the CL due to depletion width modulation. The limited evidence we do have is suggestive of the expected

behaviour. Further complications would arise from carrier screening effects should the carrier density be very high. Out of interest, if we apply the model described by Goulding to our samples and experimental observations, then the results are in reasonable agreement with 'theory'. We have equated the CL cut-off point (signal detection limit) to the dead layer thickness: this is where the integrated CL signal strength is 10^{-3} of the peak value. In which case, the experimentally detemined dead layer thicknesses were found to be 600 Å at 300K and 250 Å at 15K, which compares with values of 400 Å and 100 Å, respectively, determined from the above model.

G.V. Saparin: Can you account for the dark aureole in Fig.5(b) by considering edge scattering effects and conductivity differences between the substrate and contamination layer: the aureole dimensions would then be dependent on the primary beam energy?
Author: It is rather difficult to estimate the film thickness and conductivity (especially since the 'contaminant' composition is not presently known) at the low temperatures used in these experiments. Therefore, we are not able to comment on this matter.

G.V. Saparin: Can you estimate d_c (the contamination layer thickness)?
Author: Owing to the relatively small area of material exposed we are not in a position to measure the thickness by, for example, ellipsometric techniques.