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SPECTRALLY RESOLVED TRANSMISSION CATHODOLUMINESCENCE EVALUATION OF VERTICAL CAVITY SURFACE EMITTING LASERS

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Abstract

We describe an inexpensive addition to an existing cathodoluminescence system: Spectrally resolved transmission cathodoluminescence (SRTCL). In this technique, we couple the light emerging from beneath the sample into a vacuum compatible fiber optic cable for spectral dispersion by a conventional spectrometer. This simple approach represents a new development in the area of cathodoluminescence characterization. This exploratory study describes the preliminary results of this effort. We have applied SRTCL to the evaluation of InGaAs quantum wells, grown by molecular beam epitaxy, in vertical cavity surface emitting lasers . Results thus far support the viability of the technique. We also discuss the difficulties experienced to date and provide suggestions for future system improvements.

Key Words: Transmission cathodoluminescence, spectral dispersion, surface emitting lasers, quantum wells, fiber optic cable.

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Introduction

The application of panchromatic transmission cathodoluminescence (TCL) in depth evaluation or volume probing of semiconductor materials and devices has been described by a number of workers [1,2,3,6]. TCL refers to the situation where light generated by an electron beam in the top surface region of a sample is detected beneath the specimen following transmission through the bulk. The technique provides an easy and relatively cost-effective means of implementing the cathodoluminescence contrast mode onto a scanning electron microscope (SEM). The use of filters in conjunction with different solid state detectors (Si or Ge, typically) can provide a limited energy-filtered capability, i.e. spectrally resolved images. A natural extension to this approach would be the implementation of true spectral differentiation. In this article, we describe a simple addition to an existing emission cathodoluminescence (ECL) system which can perform spectrally resolved transmission cathodoluminescence (SRTCL) measurements. The potential uses of SRTCL would at first seem somewhat limited owing to strong optical absorption in the bulk. This causes the exiting light to be both weak and perturbed in nature. However, a number of specialized and custom applications can be envisaged. Here we apply the technique to the evaluation of buried InGaAs quantum wells in vertical cavity surface emitting laser structures (VCSEL) [4]. Such structures are ideal for SRTCL studies since the laser light can be designed to exit through the bottom of the device and the quantum well emission is also at a wavelength that is not particularly absorbed by the GaAs substrate. We describe the implementation of the SRTCL technique, compare ECL and TCL, and present some preliminary results from the specialized laser structure.

Experimental

The SRTCL system was designed around our

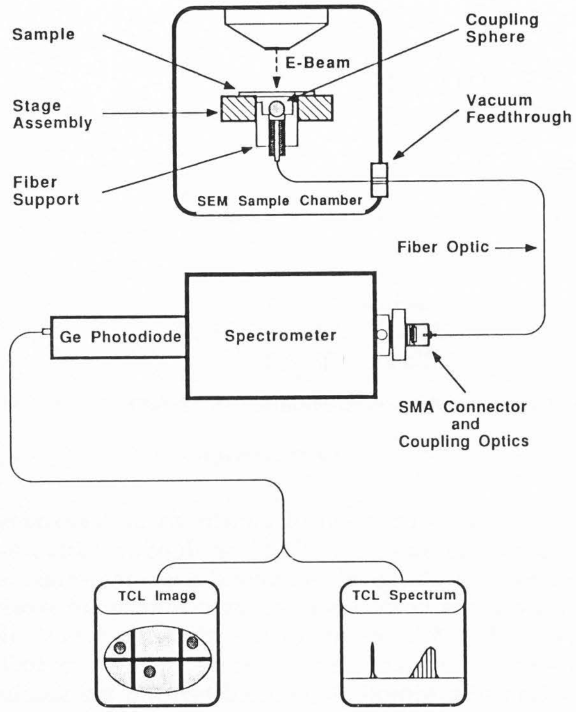

Figure 1. Schematic of SRTCL experimental setup.

existing CL set-up implemented on a JEOL 840 SEM [7]. The SRTCL system uses a fiber optic cable to couple the transmitted light to the external spectrometer system. For this purpose, we used a Newport FC-2UV multimode 200 µm diameter fiber optic cable in conjunction with a Newport F-VCF vacuum feedthrough [5]. This feedthrough utilizes a standard 2.75 inch CFF stainless steel mounting flange. This flange was then welded to a modified half-nipple CFF mounting flange, which was then mounted on to the spare secondary electron detector port on the JEOL. This particular port was chosen simply because it was free: all the other ports on the SEM were already committed to various detectors, analyzer facilities, and cold stage. This additional vacuum feedthrough to the SEM did not degrade the baseline vacuum of the instrument (4×10^{-6} torr). Internal to the system, we used a glass coupling sphere (uncoated, 5mm diameter and 0.25 mm focal length) to improve light collection into the fiber. For structural support we glued the fiber into a stainless steel tube with a special epoxy. The epoxy cement was composed of the following components; DER 331 (Dow Chemical) cement and VERSAMID 140 (General Mills) hardener, mixed by weight in approximately a 50/50 ratio. Although this epoxy was specifically designed for cryogenic applications, we found the viscosity appropriate for the placement of the fiber into the stainless steel tube. The exposed end of the fiber was subsequently diamond polished. This support tube was then attached to another assembly beneath the sample stage. The low profile of this attachment was such that it did not interfere with the normal operation of the stage, i.e. if one wished, the fiber-assembly could be a permanent fixture to the stage. External fiber connections to the coupling optics were of the SMA type. See Figure 1 for a schematic of the SRTCL system. In the experiments to be described, we used a North Coast EO-817L Ge photodiode for detection of both ECL and TCL signals at room temperature. We used phase sensitive detection (Princeton Applied Research 5301) for the recovery of both ECL and TCL signals, where the electron beam was modulated at 29 Hz. The VCSEL structures used in this study were grown by molecular beam epitaxy (MBE) in a Vacuum Generators V80H dual chamber reactor. A typical VCSEL structure is shown schematically in Figure 2. The heart of the device contains two distributed Bragg reflector mirrors composed of alternating layers of (AlAs) and (GaAs), which sandwiches a 80 Å $In_xGa_{1-x}As$ (x = 20%) quantum well. The respective p- and n-type doping of the top and bottom of the mirror stacks were in the range 4×10^{18} cm^{-3}. The vertical extent of this portion of the device is typically around 7 µm (mirrors, cavity and quantum well). Therefore, in order to 'excite' the entire structure we used electron energies in the range 30 - 35 keV. The samples that we investigated were not completed into final mesa structures, but had anti-reflection coatings on top and patterned gold ohmic contacts on the bottom.

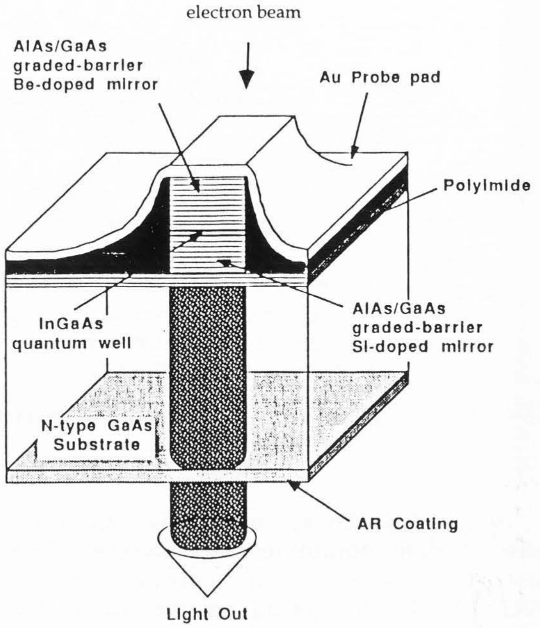

Figure 2. Schematic of a vertical cavity surface emitting laser.

Results

To begin with, we wish simply to demonstrate the strong spectral absorption that can occur (~ 10^4

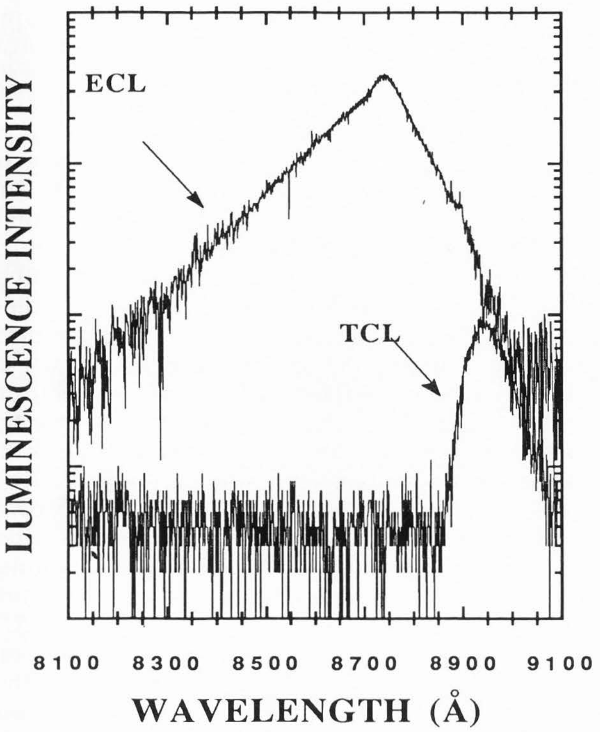

Figure 3. Comparison of ECL and TCL spectra from GaAs at 35 keV, 30 nA and 300 nA, respectively (Note: x10 difference in excitation). The spectra have been offset for clarity.

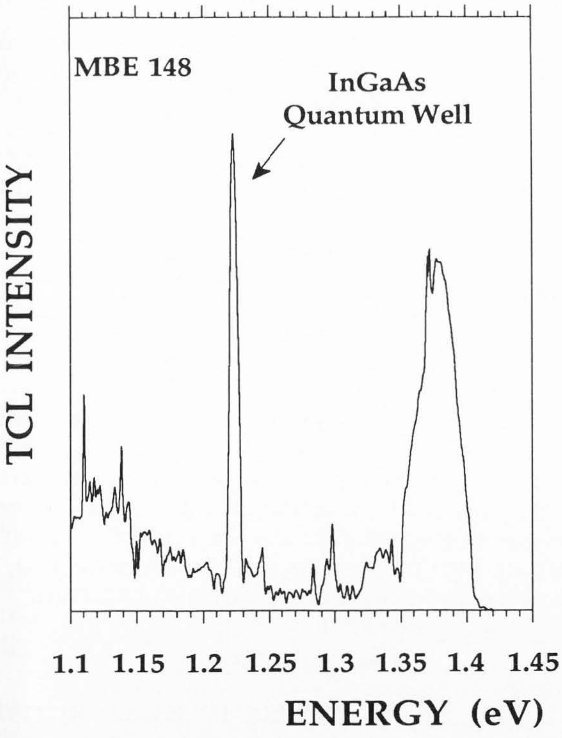

Figure 4. Room temperature TCL spectrum from InGaAs VCSEL structure (30 keV, 100 nA).

cm^{-1} at the GaAs band edge) with the as-generated cathodoluminescence prior to detection as TCL. In Figure 3, we show a comparison of ECL and TCL spectra from a heavily doped (> 10^{18} cm^{-3}) 20 μm thick MBE GaAs epilayer grown on a 400 μm thick n^+ GaAs substrate. In this particular instance, the luminescence signals were detected with a Hamamatsu R928 photomultiplier tube under the same band pass conditions, but different excitation levels. The TCL signal was acquired under ten times more beam power than the ECL. Please also note that the spectra were acquired under different circumstances: our present experimental set-up does not allow simultaneous ECL and TCL acquisitions.

In this work we have applied the SRTCL technique to two similarly processed laser structures: one of which ultimately operated, and one which did not function at all. In Figure 4, we show a TCL spectrum acquired from a working VCSEL type structure. Note that the main quantum well emission from the sample was around 1.23 eV: The fullwidth at half maximum (FWHM) of this band was approximately 6 meV, representing the spectrometer band pass used in this experiment. The designed emission energy was 1.29 eV. There was some emission detected in this region, but it was relatively weak (see figure again). The samples used in this preliminary investigation were taken from the edge of the wafer, where uniformity control of the InGaAs composition, quantum well and Bragg reflector thicknesses, is typically more difficult. Readers should note that these VCSEL device structures require very complex and stringent growth procedures. Another TCL experiment with improved spectral resolution (1.5 meV band pass) revealed that the InGaAs quantum emission was actually composed of two bands: a main band (FWHM = 4.8 meV) with a weaker sub-band 5.7 meV higher in energy. The latter sub-band was found to be injection dependent: this band is related to a higher energy transition of the structure. In passing, it is worth noting that, the ECL signal strength from the InGaAs quantum well was particularly weak relative to the GaAs band edge signal under identical excitation conditions.

In another VCSEL wafer, completed devices did not exhibit lasing characteristics. We evaluated a seperate portion of the sample, prior to mesa fabrication, by ECL and TCL. No quantum well emission was detected in either mode. See Figure 5 for a comparison of ECL and TCL spectra. In short, there was no 'optical' evidence to support the presence of a quantum well. Note also the modulation (interference) on both ECL and TCL spectra. Typically, the dielectric mirrors are designed for optimal reflection at the center wavelength of the laser. Side lobes are typical in the spectral reflectance properties of the distributed Bragg reflector laser cavity. It is probable that the observed modulations

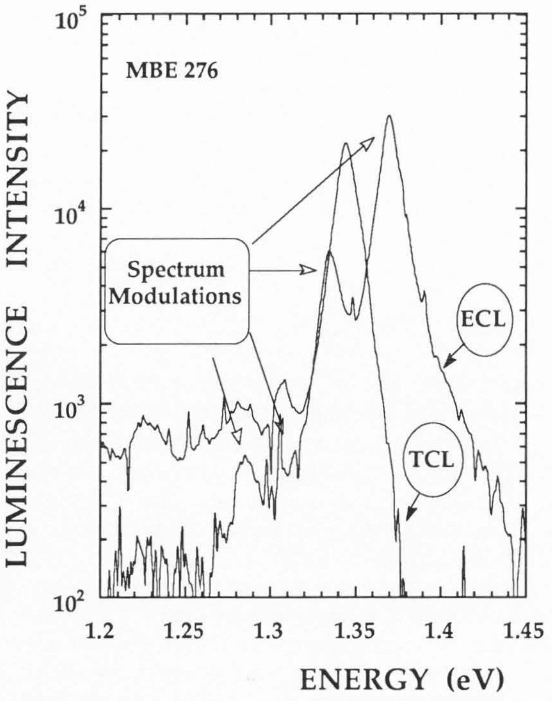

Figure 5. Comparison of room temperature ECL and TCL from a different VCSEL structure (35 keV, 80 nA).

to the broad emission spectra in Figure 5 are due to this property of the laser structure.

In Figure 6, we show a comparison of panchromatic ECL, panchromatic TCL and secondary electron images from the first VCSEL described earlier. Note the differences between the ECL and TCL images. In the TCL image, we can see the shadow of the back side (gold) ohmic pad. Since this sample was not completed into a mesa structure, the surrounding material was also observed to emit light. Also note that the TCL photograph in Figure 6 was not acquired with the SRTCL set-up, but with our conventional TCL solid state detector set-up. We include this to demonstrate the imaging capability of the technique and the potential of performing simultaneous ECL and TCL, viz Figure 6 (b) and (c). With the current optical fiber, the field of view is restricted to an area approximately 150 µm in diameter. This restriction makes our current SRTCL imaging system suitable for magnifications > x 500, i.e. more suited for 'higher' resolution imaging. Our imaging experiments thus far with the SRTCL system have not detected any new cathodoluminescence contrast effects.

Discussion

We have demonstrated the practicality of the SRTCL technique, although the application was somewhat specialized. Specifically, we were able to detect the presence of optically active quantum wells. In this section we discuss some of the difficulties experienced thus far, and also make some suggestions for future improvement. The typical beam current (up to 100 nA) used in order to generate detectable TCL signals is of some concern. These power levels are in fact not unusual for room temperature ECL evaluation of semi-insulating or low doped GaAs material. Improvement in the coupling efficiency of the TCL into the fiber would help this situation. For example, it would be much easier to focus the TCL into a 1mm diameter fiber bundle than our present 200 µm fiber. This would also increase the field of view. Low temperatures generally enhance the luminescence efficiency of many transitions compared with room temperature. Incorporation of a TCL assembly into a cold stage system would not be an unreasonable task to accomplish. Both these steps (larger diameter fiber and lower temperatures) would reduce the power requirements for SRTCL. The choice of fiber material, with respect to spectral response (attenuation versus wavelength), limits the detection wavelength range of the system. The silica FC-2UV fiber used in this investigation is actually more suited to the ultra-violet part of the spectrum rather than to the infra-red to which we directed our attention. On this point, please also note that the transmission properties of the fiber were not responsible for the modulations observed in the spectra of Figure 5.

Conclusion

We have demonstrated that a simple and cost-effective, spectrally resolved transmission cathodoluminescence system can be added to an existing CL set-up. We have applied the technique to the evaluation of specialized vertical cavity surface emitting laser structures. In principle, provided the electron beam is able to penetrate the top metal contact and excite excess carriers in the semiconductor, the SRTCL technique can be applied to completed devices.

Acknowledgements

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Discussion with Reviewers

D.B. Holt: This is a nice new technique but how widely applicable do you think it is likely to be? Quantum wells are outstandingly good for CL since they emit very strongly and have well understood spectral characteristics. Clearly quantum wires and dots are other potential objects for study by this technique but are there others, perhaps among epitaxial multilayer device structures?

Authors: As stated in the text, applications of SRTCL are likely to be of a very specialized nature. The structural layout of the VCSEL we investigated was ideal for demonstration of the technique. Besides your suggestions, the technique can be useful in situations where the top surface interferes with emission, for example, presence of overlayers (metal, dielectric, polyimde, etc.). Other potential applications include buried layers generally, for example, HBTs, tandem solar cell structures, etc. In addition, we have also done some work on simultaneous EBIC and TCL measurements (Rowley, 1989).

J.F. Bresse: What are the physical limitations of the SRTCL and the advantages as compared with SRECL, i.e. for the detection of impurities? What modifications are required to detect TCL and ECL simultaneously?

Authors: In circumstances where detection of ECL is not possible, TCL may provide a viable alternative (light blocked by a top surface electrical contact, for example). This is provided that; (i) the electron beam can penetrate the metal barrier, (ii) generate excess electron-hole pairs in the bulk, and (iii) that bulk

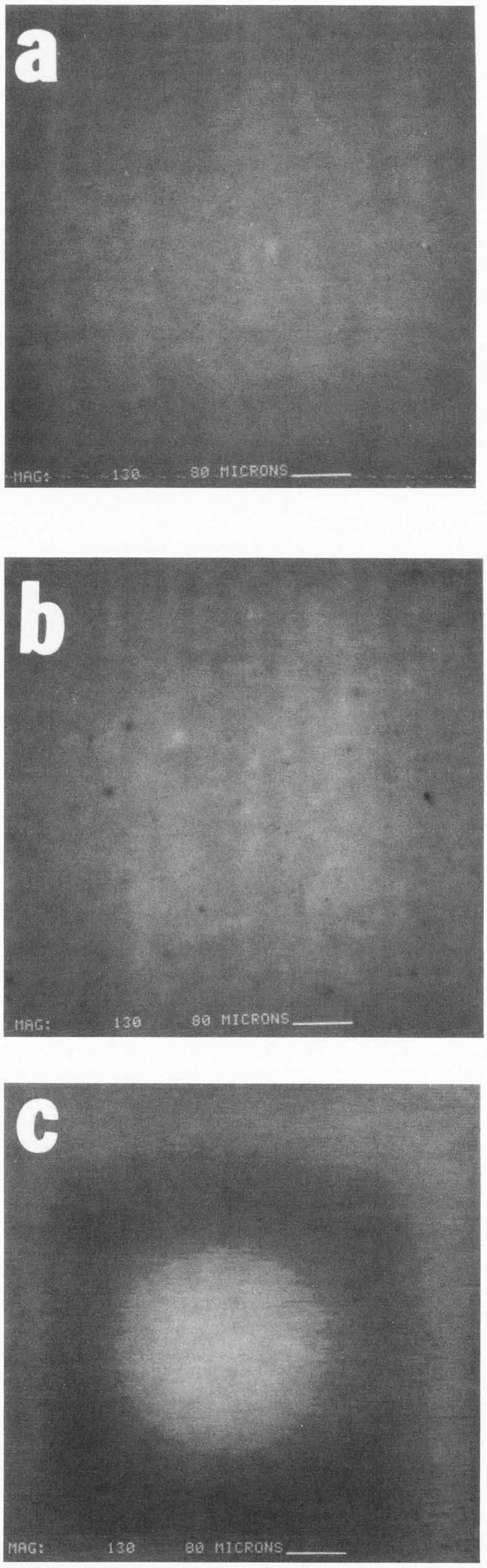

Figure 6. SEM images of a VCSEL: (a) secondary electron, (b) panchromatic ECL, and (c) panchromatic TCL. Bar = 80 μm.

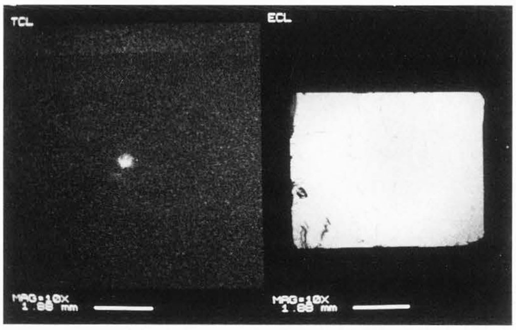

Figure 7. Comparison of panchromatic ECL and SRTCL images from GaAs substrate. This figure visualizes the transfer function of the SRTCL system. Bar = 1.88 mm.

optical absorption is not too excessive (related to sample thickness). See Figure 3 again as a reminder of absorption effects. On your second point, we feel that in principle detection of impurties would be possible at cryogenic temperatures: analogous to SRECL.

We performed the ECL measurements on a different and quite seperate CL cold stage system, though the spectrometer and detection instrumentation used were common. To be able to simultaneously detect (SR) TCL and ECL with our present system would require a relatively simple re-design of the sample-cold stage mount to accommodate the fiber-coupling sphere arrangement. An 'optical' switching arrangement could be envisaged for directing the TCL and ECL signal in a sequential time correlated fashion into the (common) detection system. The requirement for strict thermal isolation of the TCL collection optics from the sample mount would present the major challenge in the design. On the other hand, we are currently able to perform simultaneous panchromatic TCL and ECL imaging experiments. However, this would be better performed by using detectors with comparable bandwidths: our use of solid state detectors for TCL represents a limit to 'real time' imaging. However, portable (size equivalent to solid state detectors) photocathodes are currently available. This would also alleviate any space constraints associated with the use of more conventionally sized phototubes, and match the bandwidths.

J.F. Bresse: Is SRTCL a technique which may be adapted to test the quality of the dielectric mirrors?
Authors: As a stand alone test SRTCL would be inadequate. This is because of the difficulties in analysis associated with the convoluted nature of the (CL) spectral source. However, we feel that some information could be extracted about the spatial uniformity of mirror (performance). This could be achieved by imaging at selected interference or reflectance related wavelengths. A detailed analysis of the spectral interference could provide information on layer thicknesses. However, evaluation of material quality, interface roughness, etc., would require considerable development work.

J.F. Bresse: How do you interpret the peak higher in energy than the InGaAs peak?
Authors: The low energy peak (main InGaAs emission) is attributed to the n=1 electron to heavy hole transition in the quantum well. The peak around 5 meV higher in energy is attributed to the electron to light hole transition.

A. Jakuboviz: The authors say that with the current optical fiber, the field of view is restricted to an area approximately 150 µm in diameter. Could the authors comment on the transfer function of their system, i.e. on the response as a function of beam position on the sample? Is the maximum intensity in Figure 6 a property of the structure, or does it only reflect the system's transfer function?
Authors: The transfer function can best be visualized from the images in Figure 7. These images were derived from a very heavily doped GaAs substrate. The SRTCL signal (left photograph) originates from a small area of the sample. This should be compared with the uniform nature of the panchromatic ECL signal (right photograph). Now with reference to the TCL image in Figure 6, we re-iterate that the SRTCL system was not used in that instance. Therefore, the image does not reflect the system's transfer function.

A. Jakuboviz: The authors say that typical beam currents up to 100 nA are needed. In device studies, often, low excitation is required to prevent irreversible changes of the device parameters. Could the authors comment on this?
L.J. Balk: In our work, we have found that relatively low beam currents (of less than 10 nA) can considerably damage III-V compound semiconductor devices of similar type as discussed in your paper. What chances do you see realistically to reduce your primary current to such a level?
Authors: We agree that the currents used are somewhat high, and that irreversible changes to device characteristics can occur. Catastrophic damage would certainly occur were the beam power be sufficient to cause arsenic evaporation from the crystal. The limitation on minimum usable beam current is the luminescence efficiency of the active region and the collection-detection efficiency of the optical system. On this latter point, our system sensitivity could be improved by replacing the solid state Ge detector with an appropriate higher efficiency photomultiplier tube, for example, a single photon counting InGaAs photocathode.