

# Nondestructive electroluminescence characterization of as-grown semiconductor optoelectronic device structures using indium–tin–oxide coated electrodes

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We describe an arrangement for nondestructive electroluminescence measurements to characterize as-grown semiconductor optoelectronic device structures using indium–tin–oxide film coated on glass as a separate transparent electrode. The usefulness of this technique, and its applicability over a range of temperatures, are demonstrated by measurements on pieces of bare as-grown wafers of two different laser structures. © 2000 American Institute of Physics. [S0034-6748(00)01604-X]

Postgrowth characterization of semiconductor optoelectronic device structures to determine composition and quality of active regions is usually done using photoluminescence (PL) spectroscopy.<sup>1</sup> Although nondestructive, PL has several drawbacks: the sample usually needs to be cooled to get sufficiently strong signals; due to the wide range of active region band gaps possible, excitation lasers of different wavelengths are needed; and, even so, a PL measurement may be impossible if the laser is appreciably absorbed in any narrow band gap overlayers. Since most device structures have a  $p$ – $n$  junction at the active region, electroluminescence (EL) can in principle give identical information about the active region, even above room temperature. However, EL normally requires deposition of metallic electrodes onto sample surfaces, making it a destructive technique, and the electrodes themselves partially block EL emitted from these surfaces so that its detection may require large, potentially damaging currents.

Indium–tin–oxide (ITO) films are often coated directly onto device structures to form transparent conducting electrodes. We have experimented with ITO-coated glass slides, as a separate transparent electrodes, in order to perform post-growth EL characterization. Figure 1 shows the construction of the sample holder, which consists of a grounded L-shaped copper bottom electrode, with two threaded holes. The base can be clamped to a flat surface, such as a cryostat cold head. The top electrode is made of a glass slide coated on one surface with an ITO film (sheet resistance 20  $\Omega$  per square). The uncoated surface of this slide is glued to a copper plate which has a large central perforation to let light through. The sample is first placed on the bottom L-shaped electrode and then the top electrode assembly is lightly pressed on to it so that the ITO film touches the sample's surface. Since the ITO film is electrically isolated from the perforated copper plate to which the glass slide is glued, it is possible to screw this plate onto the bottom electrode using copper screws, with the sample thus sandwiched in between the electrodes. The glass slide extends beyond the width of the copper plates, so that a thin copper wire can be electrically connected to the ITO with conducting silver epoxy. Copper improves thermal con-

ductivity for experiments above and below room temperature.

This arrangement does not damage the sample in any way, though there is a much larger contact resistance than with direct metallic coating of samples. The arrangement allows EL emitted from the front surface of the sample to be easily detected through the ITO electrode. However, the edge of the sample is also optically accessible, allowing detection of any EL emitted in this direction (i.e., in the plane of the electrodes). As will be shown later, this proved very useful. However, caution is necessary in this geometry, since front-emitted EL can be wave guided by the glass slide and detected simultaneously. In certain device structures—especially vertical cavity surface emitting lasers (VCSELs, see later)—this would be undesirable since the EL spectra emitted in these two orthogonal directions have very different line shapes. To prevent this, the edges of the ITO coated glass slide were painted over.

Here, we used this arrangement to study pieces of bare as-grown wafers (area  $\approx 4$  mm $\times$ 4 mm) of two unprocessed laser device structures, both designed to operate at red wavelengths, though the technique is applicable over the transparency window of ITO on glass (typically  $\approx 400$ –2000 nm). The first sample was a  $\text{Ga}_x\text{In}_{1-x}\text{P}/(\text{Al}_y\text{Ga}_{1-y})_{0.52}\text{In}_{0.48}\text{P}$  quantum well (QW) edge emitting laser (EEL) structure. Without destructive etching, no PL signal could be obtained from its active region due to absorption of the pump laser beam in the top cladding and cap layers. In stark contrast, it was trivially easy to obtain EL using our new arrangement. Figure 2 shows a current–voltage (across the electrodes) characteristic of this sample. The differential resistance in the forward conduction region is  $\approx 1.3$  k $\Omega$  most of which must be due to the contact resistance which depends on the sample and mounting. The EL was measured at room and low temperatures, and, to improve thermal conductivity, the sample was attached to the ground electrode using conducting silver paste (soluble in acetone). In such  $p$ – $n$  junction samples, EL can be excited using either a pulsed current or voltage source, and measured on a standard PL setup<sup>1</sup> using a lockin amplifier (LIA). However, many modern LIAs have internal oscillators whose sinusoidal voltage output can conveniently be used to excite the EL, although this occurs only

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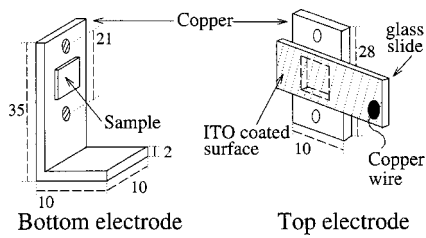


FIG. 1. Schematic of the sample holder for nondestructive electroluminescence measurements. All dimensions are in millimeters.

in the positive cycle when the  $p-n$  junction is forward biased, as shown in the inset of Fig. 2. Since the contact resistance varies with mounting, it is advisable to amplify the LIA output voltage externally, which will also protect the LIA internal oscillator in case of an accidental short circuit. Figure 3(a) shows the EL spectra recorded with a peak voltage and current of 5 V and 50  $\mu\text{A}$ , respectively. Such currents are too small to cause any sample damage. These spectra clearly reveal the energy of the ground-state QW transition at room temperature, and its expected blue shift on cooling, demonstrating the low temperature capability of this arrangement. The upper working temperature of this arrangement is limited to  $\approx 150^\circ\text{C}$  because of the epoxy used to make electrical contact to the ITO film.

Figure 3(b) shows a second interesting case; that of a red VCSEL structure with two  $\text{Al}_{z_1}\text{Ga}_{1-z_1}\text{As}/\text{Al}_{z_2}\text{Ga}_{1-z_2}\text{As}$  distributed Bragg reflector (DBR) stacks sandwiching a Fabry–Perot laser cavity containing  $\text{Ga}_x\text{In}_{1-x}\text{P}/(\text{Al}_y\text{Ga}_{1-y})_{0.52}\text{In}_{0.48}\text{P}$  QWs. The DBRs achieve the high reflectivity ( $R$ ) spectral region, referred to as the stop band, within which lies a dip [weak feature at 670 nm in Fig. 3(b)(i)] corresponding to the single allowed Fabry–Perot cavity mode at the desired VCSEL operating wavelength. To achieve working VCSELs it is crucial that the wavelength of the cavity dip be in resonance with that of the peak of the QW emission.<sup>2</sup> In practice, such stringent growth requirements are often only achieved on parts of the wafer, so it is important to be able to find such regions using nondestructive techniques. However, the  $R$  spectrum strongly modulates any EL emission from the front/back surface so that such measurements give little clue as to the true position or width of the QW emission. An example is shown in Fig. 3(b)(ii), where the front-emission EL shows several misleading

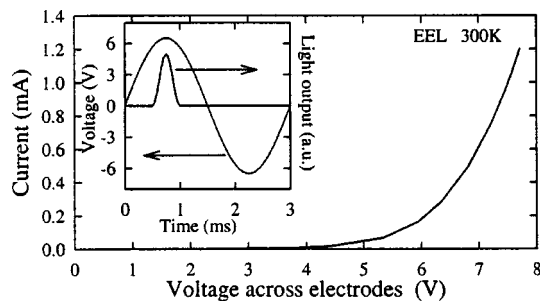


FIG. 2. The current–voltage characteristics of an as-grown laser structure placed in the sample holder. The inset shows the light output as a function of time with respect to an applied sinusoidal voltage.

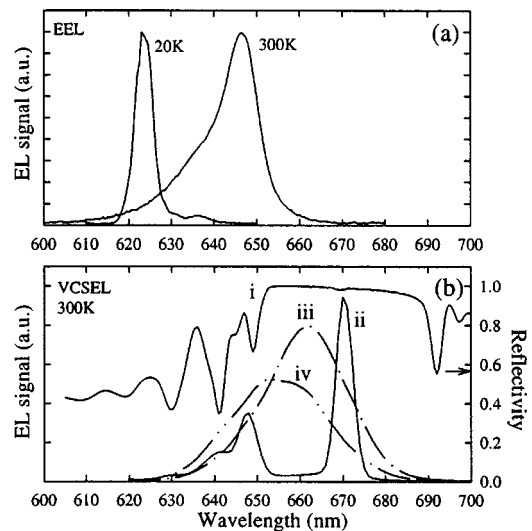


FIG. 3. (a) EL spectra of an as-grown EEL structure at two different temperatures, normalized to same peak height. (b) (i) Reflectivity and EL spectra from (ii) front, (iii) edge (TE polarized), (iv) edge (TM polarized) of an as-grown VCSEL structure. For clarity curve (iv) has been amplified by a factor of 5.

peaks, coinciding with the cavity dip and subsidiary interference minima in  $R$ . However, with the present arrangement it was possible to detect sufficient EL coming out of the edge of the sample with greater ease than in a typical PL experiment in this geometry. Plots (iii) and (iv) of Fig. 3(b) show the TE and TM polarized edge-emission EL, respectively, where TE polarization lies in plane of the QW (the same as the plane of the sample) and TM perpendicular to it. Observation of TM polarized emission is impossible with front-emission EL. These spectra are not modulated by the cavity-DBR structure, and give an estimate of the true QW emission peak position and width. The separation of the TE and TM peaks can also give an estimate of the strain in the QW, which is another crucial parameter for VCSELs and EELs. Note, however, that due to reabsorption effects,<sup>3</sup> the peak of the edge emission EL is usually slightly red shifted with respect to that which would be emitted from the front surface. In the present VCSELs we corrected for this by studying the red shifts (average  $\approx 5$  nm) which occurred in EELs grown with identical active regions to the VCSELs.

In conclusion, we have described an arrangement for performing nondestructive EL measurements, over a wide range of wavelengths and temperatures, and demonstrated its usefulness in postgrowth characterization of semiconductor laser structures. The technique has several significant advantages over PL in the characterization of optoelectronic device structures containing a  $p-n$  junction, the only drawback being that it requires a more elaborate sample holder.

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