Surface photovoltage spectroscopy characterization of a GaAs/GaAlAs vertical-cavity-surface-emitting-laser structure: Angle dependence

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An angle-dependent surface photovoltage spectroscopy (SPS) study has been performed at room temperature on a GaAs/GaAlAs-based vertical-cavity-surface-emitting-laser (VCSEL) structure emitting at a wavelength near 850 nm. For comparison purposes, we have also measured the angle-dependent reflectance (R). The surface photovoltage spectra exhibit both the fundamental conduction to heavy-hole (1C–1H) excitonic transition and cavity mode plus additional interference features related to the properties of the mirror stacks, whereas in the R spectra only the cavity mode and interference features are clearly visible. The energy position of the excitonic feature is not dependent on the angle of incidence, in contrast to that of the cavity mode, whose angular dependence can be fitted with a simple model. This study demonstrates the considerable potential of angle-dependent SPS for the contactless and nondestructive characterization of VCSEL structures at room temperature. © 2001 American Institute of Physics. [DOI: 10.1063/1.1418027]

Vertical-cavity-surface-emitting lasers (VCSELs) have several specificities compared to the conventional edge-emitting laser, including single longitudinal mode operation, small beam divergence, low threshold current, and ease of integrability and testability.1–3 A VCSEL consists of an active region sandwiched between two multiplayer distributed Bragg reflector (DBR) stacks which form highly reflecting mirrors with a broad reflectance stop band centered on a certain free space wavelength, λ_{Bragg}. Generally, both DBR stacks are highly doped, the upper p type and the lower n type, so that the whole structure forms a p–i–n diode. The central intrinsic active region consists of a barrier material with embedded quantum-well (QW) layers. The overall optical thickness of this active region determines the approximate cavity length, which is usually a few integer multiples of half of the intended lasing wavelength λ_{cav} (photon energy E_{cav}). Interaction of the DBRs and the cavity produces a sharp Fabry–Pérot dip in the reflection at λ_{cav}, usually positioned at the center of the stop band. The fundamental conduction to heavy-hole excitonic transition 1C–1H (E_{1C–1H}), which occurs at wavelength of λ_{OW}, provides the gain. To enhance this effect, the peak gain and the cavity mode are matched and the QWs are placed at the antinodes of the cavity mode. To achieve optimum performance in addition to band structure engineering aspects, several simple geometrical considerations need to be satisfied. For good laser performance, it is necessary that the condition λ_{OW} = λ_{Bragg} = λ_{cav} is realized at the operation temperature of the laser. This means that λ_{OW} at room temperature is chosen somewhat shorter than the other two wavelengths. This offset accounts for the local temperature increase. In order to characterize an epitaxial structure before laser processing, methods for the rapid determination of the excitonic transition of the QWs, cavity mode, and the thickness of the quarter wavelength layers in the DBRs are required.

The nondestructive characterization of VCSELs presents a considerable challenge, since photoluminescence,4 a technique that has been employed to characterize edge-emitting lasers, is not very useful for VCSELs because of the high DBR reflectivity. λ_{cav} can be measured using normal-incidence reflectivity.6–8 Recently Huang et al. reported a temperature-dependent surface photovoltage spectroscopy (SPS) characterization of an InGaAs/GaAs/AlGaAs VCSEL structure.9 It shows that SPS resolves both the gain providing 1C–1H transition and the lasing-wavelength-related cavity mode, E_{cav}, as well as a rich oscillatory structure above ~1.37 eV due to interference effects from the DBR stacks. The measured surface photovoltage (SPV) spectrum is also in good agreement with the calculated dependence of the photoexcited carrier density on photon energy. Thus, SPS has been demonstrated to be a contactless technique to resolve all of these features in one measurement, and it also allows for a temperature-resolved determination of these quantities. However, the qualification of device structures by temperature-dependent measurement is inconvenient for wafer-sized...
samples and not easy to use. Methods for the characterization of VCSELs at room temperature are highly desirable.

We report a comprehensive SPS and reflectance (R) study of a GaAs/GaAlAs VCSEL structure as a function of incident angle. The SPV spectra exhibit both 1C–1H excitonic transition and cavity mode, whereas in the R spectra only the cavity mode is clearly seen. The additional interference features are related to the properties of the mirror stacks. The energy position of the excitonic feature is not dependent on the angle of incident, in contrast to that of the cavity mode. These results demonstrate that angle-dependent SPS is a powerful, nondestructive tool to characterize wafer scale VCSELs at room temperature.

The VCSEL was grown by metalorganic chemical vapor deposition on an n+ -GaAs (001) substrate, and consisted of an active QW gain region embedded between two DBRs. The mirrors consist of a 30 period Ga0.08Al0.92As/Ga0.38Al0.62As n-doped high-reflectivity DBR and a 19 period Ga0.08Al0.92As/Ga0.88Al0.12As p-doped output DBR. The active region contained three undoped 60 Å GaAs wells and 80 Å Ga0.7Al0.3As barriers, centered in Ga0.7Al0.3As/Ga1-xAlx As (x = 0.3 to 0.6) spacer layers to form a single wavelength cavity. 613 Å Ga0.02Al0.98As layers were placed in the VCSEL structure above and below the active region for selective lateral oxidation to provide optical and electrical confinement. The emission wavelength for fabricated VCSEL devices is in the range of 845–855 nm. The threshold current is about 0.2–0.4 mA with an aperture size from 4.2–6.2 μm in the devices.

In SPS, the contact potential difference between the sample and a reference grid electrode is measured in a capacitative manner as a function of the photon energy of the probe beam by holding the grid fixed and chopping the probe beam at 193 Hz. The light from a 150 W quartz-halogen lamp was passed through a 0.2 m grating monochromator and focused onto the sample. The incident light intensity was maintained at a constant level of 10−4 W/cm² by means of a procedure similar to that reported in Ref. 10. A beam splitter was placed in the path of the incident light. The intensity of this radiation was monitored by a power meter and was kept constant by a stepping motor connected to a variable neutral-density filter, which was also placed in the path of the incident beam. Since our measurements were performed over a rather narrow photon energy range, constant intensity is essentially equal to constant photon flux. The induced SPV on the metal grid was measured with a metal bottom as the ground electrode, using a buffer circuit and a lock-in amplifier. In our case, the use of SPS for VCSELs characterization is, at heart, nothing more than an emulation of an absorption formalism. The reflectivity curve for 5° incident angle shows a reflectivity plateau. The inset of Fig. 2 shows the Fabry–Pérot cavity mode with higher spectral resolution. A small dip due to the resonance mode of the Fabry–Pérot cavity appears at 1.468 eV. The quality of the cavity is tested by the measured finesse, $F = E_{cav}/[2 \times \text{FWHM}] = 180$, where FWHM is full width of half maximum. Shown in Fig. 2 is a dotted line as a guide for the eye, with an arrow indicating that the cavity mode dip feature in the R spectra moves to higher energy with increase angle of incidence. The dependence of $\lambda_{cav}$ on external angle of incidence $\theta$ can be fitted with a simple model.

To a first approximation, a VCSEL structure consisting of two DBRs and a cavity can be considered as an etalon of effective thickness $d$ and mean refractive index n. The cavity mode dip feature in the R spectrum occurs at a wavelength
our reflectivity measurements can be expressed as 6

\[ R(\theta) = \frac{1}{1 + \frac{2\lambda_{\text{cav}}}{n \sin \theta}} \]

where \( m = 1, 2, 3, \ldots \).

Figure 3 summarizes the results of the angle-dependent SPS and \( R \) measurements. The closed triangles are energies of the 1C–1H excitonic transitions determined from SPS. The open circles and closed diamonds are the energies of cavity mode determined from SPS and \( R \), respectively. It may be seen that \( E_{1C-1H} \) of a QW deduced from the SPV spectra remains fairly constant with the incident angles larger than 15°. The values for the cavity mode determined from SPS agree well with the corresponding results deduced from the \( R \) spectra. The dotted curve is a guide for the eye and shows that the cavity mode moves steadily from low to high energies with an increasing angle of incidence. The results give us the information of the relative wavelengths of \( \lambda_{\text{QW}} \) and \( \lambda_{\text{cav}} \) which is of importance to the manufacturer, to check that growth has met the specifications, before committing to the expense of full device fabrication and processing, and to aid in growth calibration.

In conclusion, we have performed a comprehensive angle-dependent SPS and \( R \) investigation of a GaAs/GaAlAs VCSEL structure. The SPS spectra exhibit both 1C–1H exciton and cavity mode whereas in the \( R \) spectra only the cavity mode is clearly visible. The angular dependence of the cavity mode can be fitted with a simple model, while the energy position of the exciton feature is not dependent on the angle of incidence. Our results demonstrate that angle-dependent SPS can yield a considerable amount of information about a VCSEL structure at room temperature. The characterization of VCSEL wafers by angle-dependent SPS and \( R \) allows one to obtain detailed information about excitonic and cavity properties, and to assess whether a VCSEL wafer is suitable for devices fabrication—i.e., if the requirement \( \lambda_{\text{QW}} = \lambda_{\text{Bragg}} = \lambda_{\text{cav}} \) is met.

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