Growth of GaAs-based VCSEL/RCE Structures for Optoelectronic Applications via Molecular Beam Epitaxy

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ABSTRACT

High intensity and sharp emission peaks, at light-hole (842 nm) and heavy-hole (857 nm) excitonic transitions for a 90 Å GaAs quantum well (QW) were observed for vertical-cavity surface-emitting laser (VCSEL) structure. Excellent wavelength selectivity and sensitivity were demonstrated by resonant cavity enhanced (RCE) photodetector at 859 nm, corresponding to the energy level of a 95 Å GaAs quantum well.

INTRODUCTION

The success of generating coherent emission from gallium arsenide (GaAs) junction by a group in the Massachussets Institute of Technology (MIT) Laboratories (Quist et al., 1962) for the use of transmitting information over considerable distances in the early 1960s paved way for the slow, but continuous scientific and engineering development of emitters and photodetectors with better capabilities like efficiency, speed, and miniaturization, which started the current trends in optoelectronics technology (Hall et al., 1962; Holonyak Jr. & Bevacqua, 1962; Nathan et al., 1962). Presently, with the ever-increasing influence of the Internet, telecommunications providers around the world are replacing old copper-based telephone networks with optical fiber networks in order to satisfy the consumer demand for higher bandwidth.

Fiber-optics communication essentially uses light to carry the information through a fiber medium. The most basic requirements of this setup include an emitter to generate the light from an electrical signal, an optical fiber as the transmission medium, and a photodetector to convert the transmitted light back into electrical signal. Fiber-optics offer multi-mode (synchronous) data transfer, which allows high data transmission density using different wavelengths. This entails a rigid criterion for both emitters and photodetectors. An emitter must have high intensity and pseudomonochromatic emission while a photodetector must be wavelength selective in order to distinguish the different wavelengths transmitted through the fiber.

Alongside the development of various device structures are the improved fabricating technologies, which include Molecular Beam Epitaxy (MBE). It is a deposition technique carried out in ultra-high vacuum wherein the sources (i.e., gallium and arsenic) are evaporated and epitaxially grown (one atomic layer per second) on a relatively cooler substrate. MBE provides an excellent degree of control in the composition and smoothness of the deposited layers, which greatly affect device performance.

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THEORY

Gallium arsenide (GaAs) belongs to the III-V semiconductor compounds. It is a direct band gap material (1.424 eV) which permits highly efficient generation and detection of light. This property, and the existence of its other higher energy gap alloy like aluminum-gallium arsenide (AlGaAs) and aluminum arsenide (AlAs), makes it the most studied and highly regarded for optoelectronics applications.

The basic structure of a light-emitting diode (LED) is the p-n junction, consisting of two layers of the same band gap material (homo-junction) but with different dopants. This structure, under forward bias, emits light, and under reverse bias, detects light. Perhaps one of the noteworthy innovations in this field is the development of the heterojunction LED, wherein a thin layer of undoped lower gap material is deposited between the p-layer and the n-layer (Hayashi et al., 1970). This provides both optical and electrical confinement of photons and carriers, respectively. Incorporation of low dimensional structures in the undoped region, like quantum wells (QW), was found to greatly enhance the sharpness and intensity of the emission. Quantum wells also provide design flexibility, since its energy level (thus, the emission wavelength) can be engineered simply by varying the well width. Though the QW p-i-n structure has been successful to the point of commercialization, researchers continue to explore different device geometries. The most significant geometry is the vertical-cavity surface-emitting laser (VCSEL) or resonant cavity enhanced (RCE) photodetector. These VCSEL/RCE structures outperform other existing similar optoelectronic devices, and have only been commercially realized recently.

The VCSEL structure retains the basic p-i-n configuration, but the p- and the n-layers were replaced with highly reflecting p-type and n-type distributed Bragg reflectors (DBR). With the GaAs QW at the center, the undoped region defines the emission wavelength λ. The DBR consists of alternating layers of higher gap semiconductors, AlGaAs and AlAs, both having a thickness corresponding to $\lambda/4$. The undoped region (including the QWs) has a thickness of (multiple of) λ. This forms a Fabry-Perot resonant cavity, which is responsible for the amplification of the gain in the active region (Chow et al., 1997; Choquette & Hou, 1997; Iga et al., 1984; Unlu et al., 1991).

EXPERIMENTAL METHOD

All the samples were deposited via RIBER 32-P MBE apparatus located at the National Institute of Physics, College of Science, University of the Philippines Diliman. The samples were grown on n-type (001) GaAs substrates.

Sample P035 has a typical p-i-n structure. A 1.0 μm silicon-doped (n-type) GaAs buffer layer was grown first over the substrate, with 0.5 μm grown at GaAs surface reconstruction temperature of 580°C, and the other half ramped to 630°C. Deposition was maintained at this temperature throughout the remainder of the process. A 1.5 μm Si-doped (n-layer) AlGaAs was grown over the buffer layer, with intended doping concentration of 1.0 x 10^{18} cm^{-3}. The undoped region consists of 100 Å AlGaAs layer (barrier) and 90 Å GaAs (quantum well). A 1.5 μm Beryllium-doped (p-layer) AlGaAs was grown with doping concentration of 1.0 x 10^{18} cm^{-3}. Finally, a 100 Å Be-doped GaAs (cap layer) was deposited to serve as protective layer.

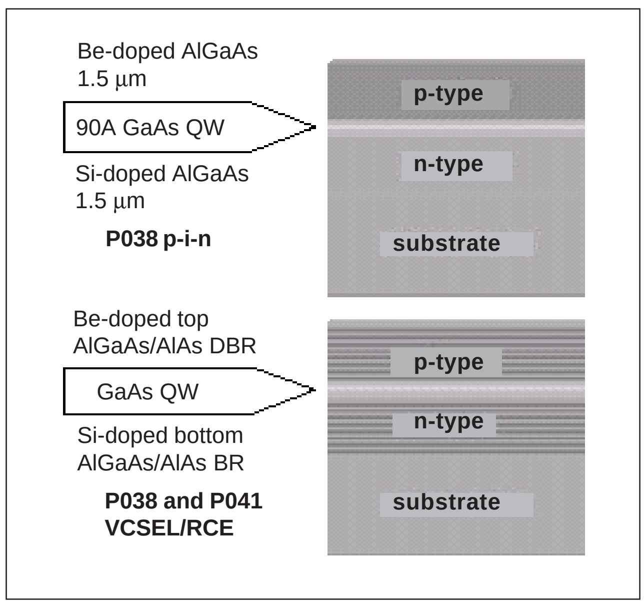

Fig.1. The structures of sample P035 (p-i-n) and the samples P038 and P041 (VCSEL/RCE).

Two samples, P038 and P041 with VCSEL/RCE structure, were also grown (Fig. 1). The 1.0 µm n-type GaAs buffer layer was grown at the same temperature as sample P035 (p-i-n). For P038, the DBR consists of AlAs and AlGaAs layers with thickness of 715 Å and 605 Å, respectively. The undoped region consists of three pairs of 60 Å AlGaAs (barrier) layer, with 90 Å GaAs (QW) and with total cavity width of 2,525 Å. For sample P041, its DBR consists of 710 Å AlAs and 623 Å AlGaAs. The undoped region consists of three pairs of 60 Å AlGaAs (barrier) and 95 Å GaAs (QW), with total cavity width of 2,440 Å. For both P038 and P041, 100 Å Be-doped GaAs cap layer was grown last.

All samples were characterized using electroluminescence (EL) spectroscopy for emission spectra and photocurrent (PC) spectroscopy for absorption. Additional reflectivity experiments were done to the VCSEL/RCE samples in order to measure the reflectance of the DBRs. Fig. 1 shows the structures of samples P035 (p-i-n) and P038 and P041 (VCSEL/RCE).

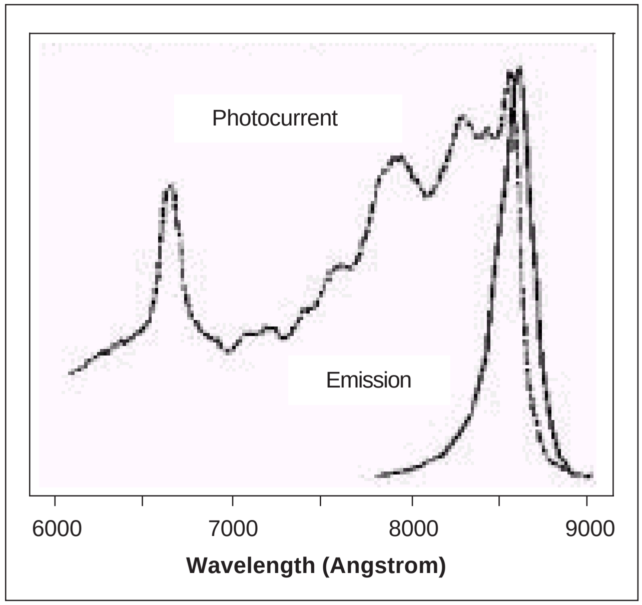

Fig. 2. The photocurrent spectra and the emission spectra of sample P035 (P-I-N).

RESULTS AND DISCUSSION

In Fig.2, the emission and the photocurrent spectrum of the sample P035 (p-i-n) is shown. The absorption spectra of P035 reveal a sharp onset of absorption at 862 nm, corresponding to the energy level of a 90 Å GaAs quantum well. At the wavelength, the emission spectra show a sharp peak with full width at half maximum (FWHM) of 110 Å. The sharpness of the rise of the absorption spectra and the high intensity emission peak is characteristic of a QW based p-i-n heterojunction.

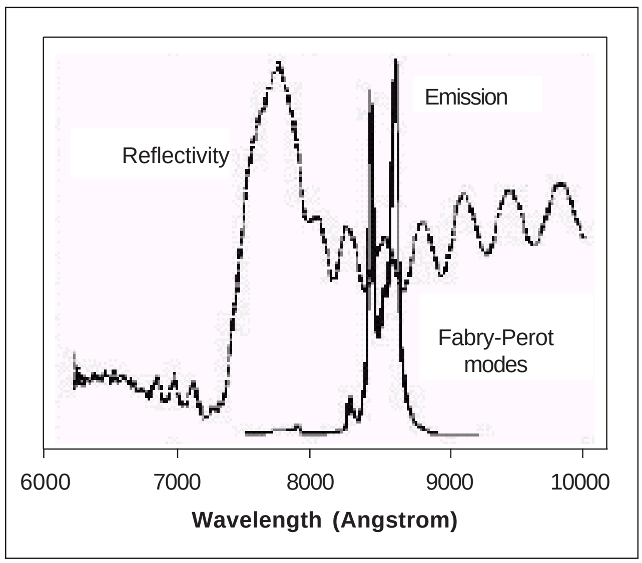

Fig. 3. The emission spectra and the reflectivity spectra of sample P038 (VCSEL) showing peak amplification by Fabry-Perot modes.

For VCSEL, its reflectivity spectra will show Fabry-Perot resonant modes and a range of peak reflectance. To maximize the resonance effect, the wavelength specified by the quantum well energy level must be within the range of maximum reflectance. Fig. 3 shows the Fabry-Perot modes and maximum reflectance from 734 nm to 795 nm in the reflectivity spectra. The emission peaks are at 842 nm and at 857 nm, both falling outside the maximum reflectance. Even if this was the case, the emission peaks were still amplified by Fabry-Perot maxima, resulting in the resolution of two distinct peaks corresponding to the light-hole (842 nm) and heavy-hole (857 nm) excitonic transitions for a 90 Å GaAs quantum well. Their FWHMs are 60 Å and 80 Å, respectively. High-intensity sharp emission peak is an important requirement for light sources of fiber optic technology.

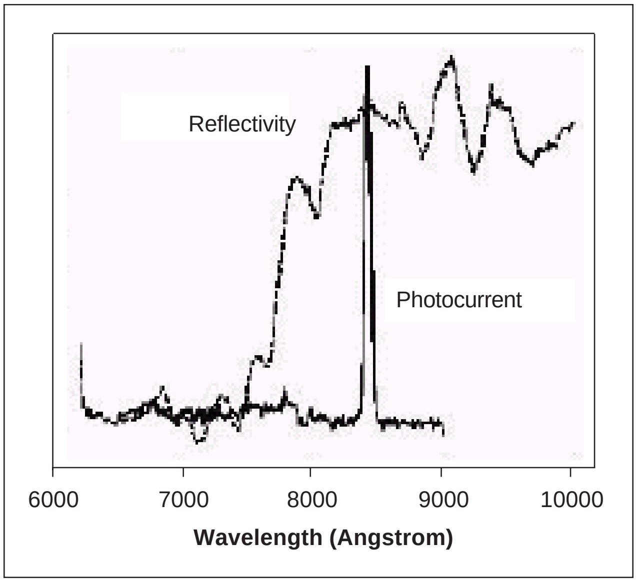

Fig. 4. The photocurrent spectra and the reflectivity spectra of sample P041 (RCE) showing peak amplification at maximum reflectance.

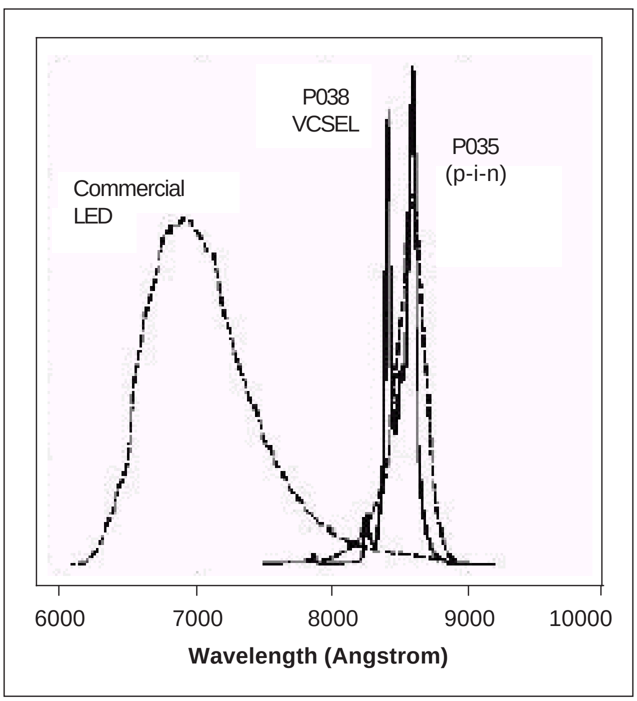

Fig. 5. The normalized emission spectra of a commercially available AlGaAs LED, the P035 (p-i-n), and the P038 (VCSEL). The spectrum of the AlGaAs LED was scaled (x25), as well as the spectrum of the P041 (x0.8), for presentation purposes. The VCSEL sample exhibited the best performance in terms of intensity and sharpness of peaks.

Fig. 4 shows the reflectivity and the photocurrent spectra of sample P041. The photocurrent spectra reveal a very sharp absorption peak at 859 nm, and FWHM of only 50 A. This is a clear indication that the grown RCE structure is highly wavelength-selective, and the high photocurrent intensity translates to high sensitivity to the specified wavelength.

For comparison purposes, the emission spectra of sample P035 (p-i-n), P038 (VCSEL), and a commercially available AlGaAs LED were plotted together in Fig. 5. The emission peaks are normalized, with the commercially AlGaAs LED showing a broad emission and has 25 times less intensity.

CONCLUSION

In conclusion, we report the results of our efforts to design and fabricate optoelectronic devices suitable for fiber optic applications. The VCSEL (P038) exhibited sharp emission peaks corresponding to the two excitonic peaks of a 90-Å GaAs quantum well, while the RCE (P041) demonstrated high sensitivity and excellent wavelength selectivity.

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