Room-Temperature Continuous-Wave Operation of npn-AlGaInAs Transistor Laser Emitting at 1.3-μm Wavelength

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***Abstract*—Room-temperature continuous-wave operation of a 1.3-μm npn-AlGaInAs/InP transistor laser is successfully achieved for the first time. A threshold current of 39 mA and an external differential quantum efficiency of 13% are obtained under common base operation, while simultaneous transistor action is achieved with a current gain β of 0.02.**

***Index Terms*—AlGaInAs/InP, quantum well laser, transistor laser.**

I. Introduction

OWING to an explosive increase in data traffic, optical transmitters have been widely studied lately. As they have advantages over electro-absorption modulated lasers (EMLs) in terms of power consumption and cost-effectiveness, direct modulation lasers (DMLs) are expected to be used more frequently in short distance optical systems. However, the modulation speed of conventional laser diodes (LDs) is limited to around 40 Gb/s owing to several factors, including damping effects caused by carrier transport [1], [2]. Such damping suppresses the resonance oscillation of LDs and, as a result, limits the modulation speed. A transistor laser (TL) based on a heterojunction bipolar transistor (HBT) with an active layer in the base region has the potential to break the modulation speed limitations inherent to LDs. Because the carriers in a TL are pulled from the emitter to the collector, they must pass the active region; as a result, the carrier diffusion time does not determine the carrier injection delay into quantum wells (QWs), allowing for fast bias modulation. Since shorter carrier recovery times can therefore be achieved, higher modulation bandwidths than those in conventional LDs can be expected [3]–[5]. Although this concept was explored in 1985 using a GaInAsP/InP bulk crystal as the active region [6], [7], transistor operation was not achieved. Since then, the first room-temperature continuous-wave (RT-CW) transistor operation of a 0.98-μm TL has been demonstrated, and some characterizations of this have been made [8]–[10]. At longer wavelengths, a wafer design [11], CW operations have been demonstrated for AlGaInAs/InP TLs at very low temperature [12], [13]. Previously, we have reported on the RT-CW operation of a pnp-AlGaInAs/InP TL with a threshold base current of 17 mA [14]. However, as the pnp configuration is not suitable for high-speed lasing operation owing to heavy hole mass within the base, an npn-configured TL is required for high-speed operation. Thus far, however, only pulsed operation at RT has been reported using the npn configuration [15].

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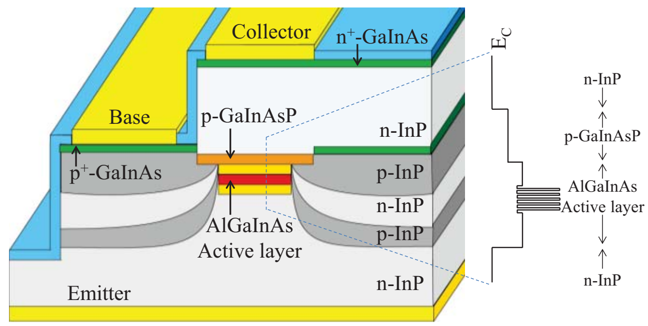

Fig. 1. Structure and the conduction band diagram of a fabricated npn-AlGaInAs/InP TL.

In this letter, we report on the first RT-CW operation of an npn-TL emitting at 1.3-μm wavelength using an AlGaInAs/InP material system.

II. Device Structure

A schematic view and a conduction band diagram of the npn-TL is shown in Fig. 1. The initial wafer was grown on a (100) n-InP substrate by using an organo-metallic vapor phase epitaxy (OMVPE) technique. The wafer consists of a 130-nm n-AlGaInAs (E_g = 1.1 eV), five fully strain-compensated AlGaInAs quantum-wells (QWs) with a wavelength of 1.3 μm, a 100-nm p-AlGaInAs, a 10-nm p-GaInAsP (E_g = 1.0 eV), and an InP cap layer. Using a SiO_2 mask, mesa stripes were

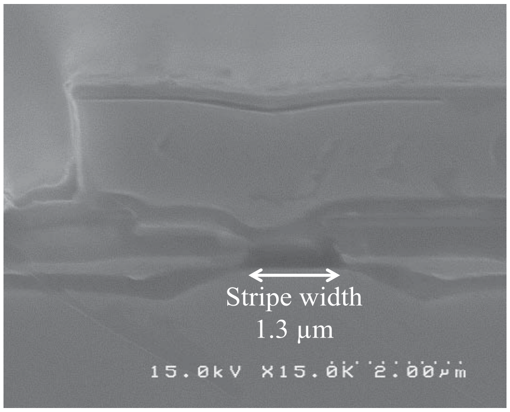

Fig. 2. SEM image of fabricated device.

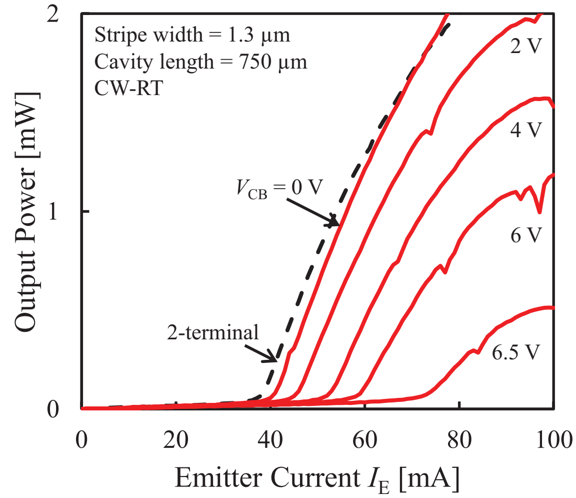

Fig. 3. Lasing characteristics of the TL under common base configuration.

formed in a two-step etching process: first, the p-GaInAsP and Al-containing layers were etched with a bromine-methanol solution (Br_2/CH_3OH = 1:1000), and then, additional mesa heights were added using a CH_4/H_2 reactive-ion-etching (RIE) process. Finally, high mesa stripes (approximately 1.0 μm in height) were formed. After mesa formation, two cleaning processes were undertaken. The first was a three-step wet cleaning process involving the addition of a solution of $Br_2:CH_3OH$ (1:40000) to clean the surface, the addition of a mixture of $H_2SO_4:H_2O_2:H_2O$ (1:1:40) to clean the Al-containing region, and finally the addition of 1% BHF to remove the oxidized layer. The device was then placed in an OMVPE reactor, where the second cleaning process, i.e., thermal cleaning, was carried out. This was done in a PH_3 atmosphere for 45 min at 650 °C—the optimal conditions for high-quality buried heterostructure (BH) AlGaInAs/InP LDs [16]. Mesa stripes with n(100 nm)/p(200 nm)/n(300 nm)/p(400 nm)-InP current blocking layers were then buried, and after removing the SiO_2 mask, a 200-nm-thick p-GaInAsP base layer (E_g = 1.0 eV) and a 50-nm-thick n-InP collector layer were regrown across the entire surface. A 6-μm-width SiO_2 mask was formed on the stripe, and then, a 250-nm-high mesa stripe was formed by p-InP-exposed reactive ion etching (RIE). This was followed by OMVPE regrowth of a 250-nm-thick p-InP, a 30-nm-thick p^+-GaInAs base contact layer, and a 50-nm-thick n-InP layer. After removing the SiO_2 mask, a 1600-nm-thick n-InP subcollector layer, a 50-nm-thick n^+-GaInAs collector contact layer, and an InP cap layer were regrown. Finally, the collector and base mesas were formed using RIE and wet etching, and the collector, base, and emitter (backside) electrodes were formed by evaporating Ti/Au (25 nm/200 nm) onto the device. Laser cavities without high reflective coating were created by cleavage. A scanning electron microscope (SEM) image of the fabricated device is show in Fig. 2.

III. Lasing Characteristics

Fig. 3 shows the current-output power ($I-L$) characteristics of a TL developed using the abovementioned process. The TL had a cavity length of 750 μm and a stripe width of 1.3 μm, and it operated in a common-base (CB) configuration under RT-CW conditions. For the reference, the I–L characteristics under 2-terminal configuration, which means emitter-base configuration with floating collector, is also shown. It should be noted that this was the first npn-TL to achieve RT-CW lasing at a wavelength of 1.3 μm using an AlGaInAs/InP material system. The threshold emitter current was 39 mA, while the external differential quantum efficiency from both facets was 13%; the calculated threshold current density was 3.5 kA/cm^2. By applying collector base voltage V_{CB}, both an increase in threshold current and a decrease in the output power were observed. We believe that this was partly because of the Franz–Keldysh effect; that is, as the effective bandgap of the p-GaInAsP base layer changed by the application of the voltage, the absorption at the p-GaInAsP base layer increased. Given that the output power of this device can be controlled by applying collector voltage, it can be expected that this device should be capable of controlling gating functions with changes in the collector voltage. Another possible cause was an Early effect. This caused the decrease of base current, therefore, higher emitter current was needed to boost base current to reach the threshold.

Fig. 4 shows a lasing spectrum of a device with a cavity length of 1000 μm at a threshold current of 43 mA under 2-terminal operation. At twice the threshold current, the lasing wavelength reached 1360 nm, and the measured longitudinal resonant mode spacing was 0.26 nm.

Fig. 5 shows the I–L characteristics of the device, which was also used in Fig. 3, using a common-emitter (CE) configuration under RT-CW conditions. Unlike in Fig. 3, the horizontal axis here represents the base current I_B. Lasing was also achieved in this case, and nearly the same threshold current (39 mA) and external differential quantum efficiency (11%) were obtained at a V_{CE} of 0 V. Unlike in the CB configuration, minimal collector-emitter voltage dependence was observed due to the small current gain explained later. The decrease of the optical power was caused by Franz–Keldysh effect.

Fig. 6 shows the dependence of the collector current I_C on the collector emitter voltage V_{CE} in the CE configuration.

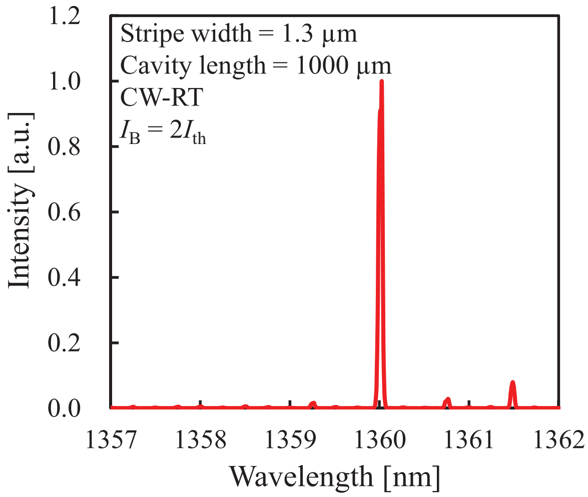

Fig. 4. Lasing spectrum of the TL.

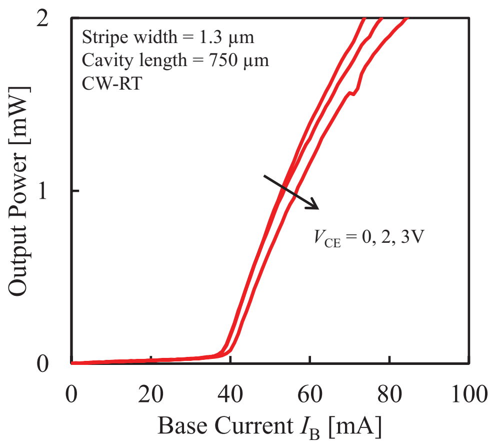

Fig. 5. Lasing characteristics of the TL under common emitter configuration.

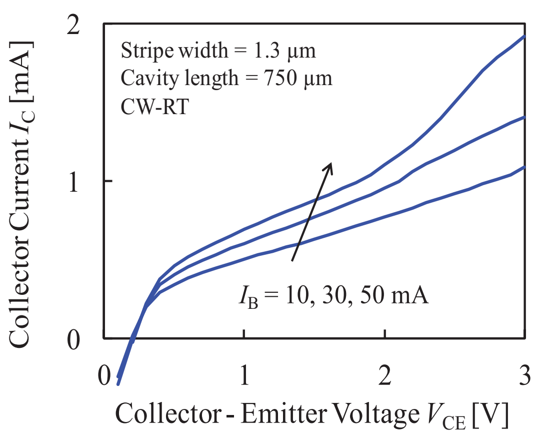

Fig. 6. $V_{CE} - I_C$ characteristics.

Under the CW operation, the base current was increased from 10 mA to 30 mA and then to 50 mA. Although a typical transistor behavior was observed, the obtained current gain ($\beta \approx 0.02$) was much smaller than that observed in the previous results [13]. As the thicker base layer reduces carrier pulling to the collector, higher current gains should be used in the future to facilitate high-speed operation.

IV. Conclusion

In this letter, we demonstrate, for the first time, RT-CW operation of an npn-AlGaInAs/InP TL emitting in the 1.3 μm wavelength region. A threshold emitter current of 39 mA and an external differential quantum efficiency at both facets of 13% were obtained. Using a common-base configuration, we were able to control the output power through the application of the collector-base voltage.

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