Passive Mode Locking of InAlGaAs 1.3-μm Strained Quantum Wells Extended Cavity Laser Fabricated by Quantum-Well Intermixing

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***Abstract*—We demonstrate continuous-wave operation and passive mode locking of extended cavity lasers fabricated in 1.3-μm InAlGaAs strained multiple quantum-wells structure. Modal losses were measured for the passive section fabricated by quantum-well intermixing. Pulse duration of 1.7 ps was deduced from intensity autocorrelation measurement.**

***Index Terms*—AlGaInAs, loss, mode-locked lasers, passive, pulse generation, quantum-well intermixing (QWI), semiconductor lasers.**

I. Introduction

THE InGasAsP–InP material system has remained unchallenged for the fabrication of long wavelength lasers over the last two decades. Making use of refined techniques like etching and regrowth and/or e-beam lithography has also led to the realization of photonic integrated devices of various complexities that may include, for example, low-loss passive sections and/or sections of different bandgaps on the single chip. Recently, aluminum-based quaternary material (AlInGaAs) has emerged as a much more promising candidate because of a large conduction band offset that leads to a better electron confinement and consequently improved intrinsic thermal characteristics. However, an undermining characteristic of aluminum-based material is that regrowth has proven to be problematic because of the spontaneous oxidation of the exposed etched layers. This limitation can nonetheless be overcome using selective quantum-well intermixing (QWI) techniques which are based on the compositional disordering between quantum wells (QWs) and barriers that causes a change in bandgap and, hence, shifts the absorption edge to higher energies. Furthermore, it is a simple, flexible, and low-cost alternative compared to selective etching and regrowth.

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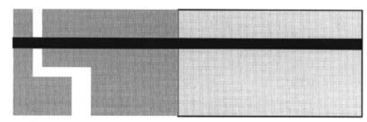

Fig. 1. Device layout of the ECL. S.A.: saturable absorber.

To date, a number of different techniques have been used to promote the intermixing in QW structures, among them impurity-induced disordering [1], ion implantation-induced disordering [2], and laser-based disordering processes [3]. The technique used in this work relies on the generation of points defects during the deposition of a sputtered silicon–dioxide film and their diffusion during a subsequent high temperature annealing treatment [4]. So far, it has been successfully employed on different III–V materials (AlGaAs–GaAs, InGasAsP–InP) to fabricate photonic integrated circuits and multisection devices incorporating different bandgaps. In the present study, we have extended its application to the fabrication of 1.3-μm strained InAlGaAs MQW passively modelocked extended cavity lasers (ECLs). These ECL laser diodes (LDs) have attracted attention because they compare very favorably to their all-active counterparts due to lower threshold current and better thermal and noise characteristics [5]. In the following, we report on the passive mode-locking characteristics of this device working at a frequency of 25 GHz.

II. Device Fabrication

The device was fabricated using the monolithic integration of active and low-loss passive sections, the latter obtained through selective QWI, as shown in Fig. 1. The active part has two electrically separated segments, a long forward biased gain section and a short section which was reverse biased to provide the necessary saturable absorption for passive mode locking [6].

The epitaxial structure was grown on a sulfur-doped InP substrate in two steps. The active region that consists of seven 10-nm barriers of lattice-matched $In_{0.52}Ga_{0.21}Al_{0.27}As$ and six 6-nm 1.4% compressively strained $In_{0.73}Ga_{0.095}Al_{0.175}As$ QWs, embedded in the $In_{0.52}Al_{0.48}As$ waveguide core, was grown by solid source molecular beam epitaxy, while the top InP Zn-doped cladding and the InGaAs contact layer were grown by metal–organic chemical vapor deposition [7].

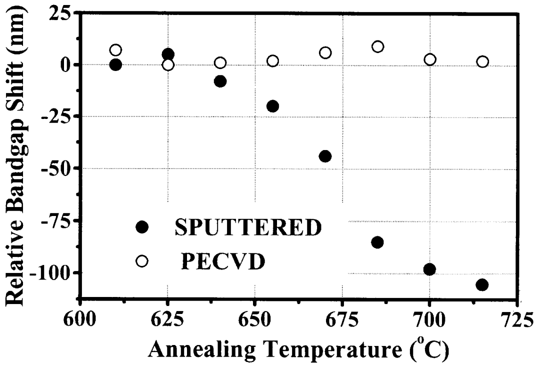

Fig. 2. Relative bandgap shift versus annealing temperature for PECVD and sputtered silica covered samples after 30-s rapid thermal annealing.

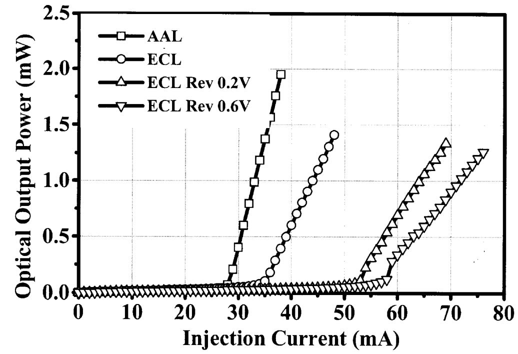

Fig. 3. L–I characteristics for a 750-μm-long AAL (□), a 1.75-mm-long ECL (O). ECL with a 0.2-V applied reverse bias (△). ECL with a 0.6-V applied reverse bias (▽).

The intermixing process was studied on two separate sets of samples, covered with plasma-enhanced chemical vapor deposition (PECVD) and sputtered SiO_2 films, respectively, and subsequently annealed in a rapid thermal annealer. The QWI process and the consequent bandgap shift were assessed by photoluminescence (PL) measurements performed at 77^0K. Fig. 2 shows the peak PL wavelength shift as a function of the annealing temperature for the two sets of samples after a 30-s annealing step. The onset of QWI for sputtered samples occurred at 600 °C and the blueshift steadily increased with the temperature to reach a maximum of 110 nm at 725 °C due the complete intermixing of the QWs and barriers. Meanwhile, PECVD-protected samples did not exhibit any significant shift over the same temperature range. Therefore, as previously demonstrated in other material systems (GaAs–AlGaAs or InGaAsP–InP), QWI can be selectively suppressed or enhanced depending on the dielectric cap employed [8].

Devices were then fabricated from samples initially covered with a 200-nm-thick PECVD SiO_2 film. This protection film was removed by wet chemical etching (HF) from selected areas to allow the deposition of a 50-nm sputtered SiO_2 film onto the sample surface. The sample was subsequently annealed at 685 °C for 40 s leading to a targeted shift of 100 nm for the passive section. The waveguide ridges, 2 μm wide, were defined by standard ultraviolet photolithography and then transferred into a 200-nm PECVD SiO_2 mask by reactive ion etching (CHF_3). Subsequently, ridge waveguides were dry etched into the epitaxial structure using a mixture of CH_4 and H_2. A 300-nm-thick passivation SiO_2 film was deposited and a contact window opened on the top of the ridge structure through to the highly doped InGaAs layer to enable a Pd–Ti–Au ohmic contact, patterned by liftoff. Following substrate thinning and the evaporation of the n contact (Au–Ge–Au), the sample was annealed at 360 °C for 60 s. The sample was then cleaved into individual devices, which were tested under continuous-wave conditions at room temperature.

III. Device Characteristics

Fig. 3 shows light output–current (L–I) curves for a 750-μm -long all-active device and an ECL with a 750-μm active section and a 1-mm-long passive section. The active section of the ECL has two separate contacts, a main contact 700 μm long and a short 40-μm contact separated by a 10-μm gap, as shown in Fig. 1. With both active sections forward biased, an ECL device exhibits a larger threshold current (34 mA) and reduced external efficiency (0.11 mW/mA) compared to an all-active laser [(AAL) 28 mA and 0.19 mW/mA, respectively], due to the propagation loss in the passive section. Because of the large blue shift of the absorption edge in the intermixed section and the absence of dopant diffusion in the intermixed QWs, free-carrier absorption in the doped cladding layers of the structure is the main loss mechanism [5]. A modal loss of 10 cm^{-1} can be estimated from the change in threshold current and slope efficiency for different ratio of passive to active section lengths [9]. Fig. 3 also shows L–I curves for different reverse bias levels applied onto the short saturable absorber.

Passive mode locking was observed by detecting the emitted light with a 45-GHz bandwidth New Focus photodiode connected to a radio frequency spectrum analyzer. Clear observation of a strong resonance at the cavity round trip frequency was identified as the signature of mode locking. The gain section length was set to a fixed length of 700 μm following the work of Piprek *et al.* [10] while the absorber and passive section lengths were defined by cleaving. Different gain/absorber ratios have been investigated and the best mode locking characteristics were obtained for an absorber length of 40 μm while devices with longer absorbers generally exhibited only self-pulsations. Finally, the passive section length was chosen so that the targeted frequency of 25 GHz could be obtained under mode-locking condition.

Two-photon absorption (TPA) intensity autocorrelation measurements were taken to assess the pulse duration. The experimental setup is shown in Fig. 4(a). The emitted light from the laser under study was first collimated by a microscope objective and then launched into a Michelson interferometer with one mirror mounted on a translation stage, to provide the fine optical delay adjustment required to perform the autocorrelation measurements. A half-wave plate was inserted in the fixed arm so that two cross-polarized beams would impinge on the TPA waveguide detector. A commercial LD, emitting at 780 nm, was used as the detector [10]. The generated photocurrent within the TPA waveguide detector was measured using a lock-in amplifier, referenced to a chopper. Fig. 4(b) shows the autocorrelation trace of the pulse train from a passively mode-locked ECL. The

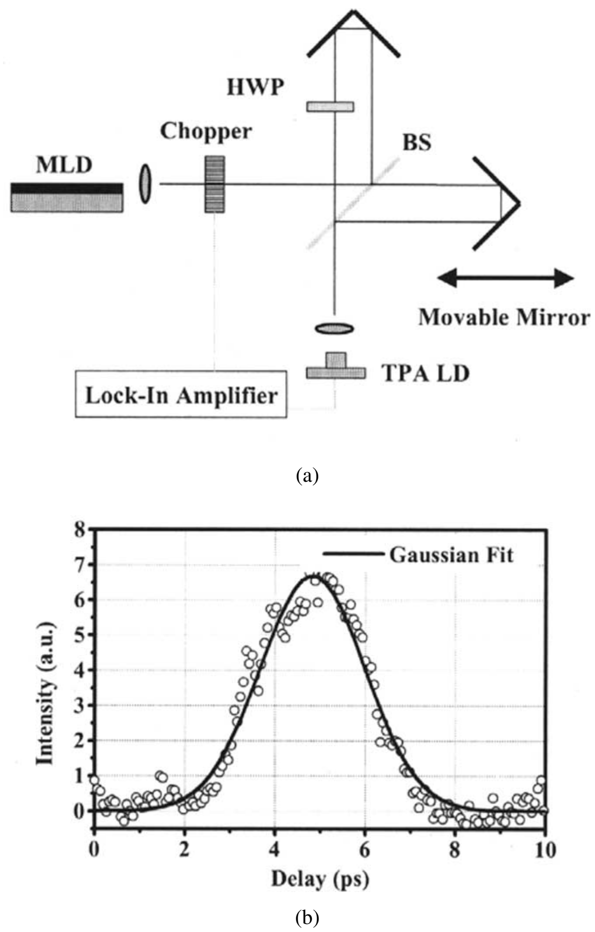

Fig. 4. (a) Autocorrelation setup. MLD: mode-locked laser. HWP: half-wave plate. BS: beam splitter. (b) Autocorrelation trace for the mode locked ECL.

injection current in the gain section was 110 mA and the reverse bias applied onto the saturable absorber 0.6 V; the pulse repetition rate was close to 25 GHz. The autocorrelation trace has a width of 2.5 ps, which deconvolves to a 1.7-ps pulse duration assuming a Gaussian pulse shape.

IV. Conclusion

We have reported the passive mode locking of 1.3-μm InAlGaAs strained MQW ECLs. Such devices integrate active and passive sections, with the latter fabricated by QWI. Modal propagation losses of 10 cm^{-1} were measured for the passive section. A pulse duration of 1.7 ps at a repetition rate of 25 GHz was determined from TPA autocorrelation measurements.

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