The room temperature, continuous-wave (CW) operation of a fabricated multi-diode cascade vertical-cavity surface-emitting laser at 980 nm wavelength, with a differential quantum efficiency exceeding unity is demonstrated. For the wallplug efficiency, the maximum of 16% is obtained at a driving current of three times the threshold.

1. Introduction

The performance of conventional vertical-cavity surface-emitting lasers (VCSELs) is generally limited by the extremely low roundtrip gain in the cavity. Thus, VCSEL devices require high mirror reflectivity but also are characterized by an increase in the threshold current density compared to edge emitting lasers. To overcome this distinct disadvantage, diode cascade VCSELs (also called bipolar cascade VCSELs) are proposed as excellent candidates to improve the performance of VCSEL structures with bulk [1] and quantum well [2] active layers. Such a VCSEL can also exhibit high differential quantum efficiency well exceeding unity that may be interesting for low noise applications. The increase in roundtrip gain is also of interest for high-power VCSEL applications. Recently, long wavelength diode cascade VCSELs with CW operation up to 6°C were reported [3]. CW oscillation with diode cascade devices at room temperature was so far only obtained at 980 nm wavelength [4, 5]. All demonstrated devices still suffered from comparatively low slope efficiencies. Recently, we fabricated the first CW room temperature operating multi-diode cascade VCSEL with a differential quantum efficiency exceeding unity [6].

2. Device Structure

Fig. 1 shows a schematic diagram of the device structure that is grown by molecular beam epitaxy. The top and bottom Bragg reflector stacks consist of 14 and 32 Al0.9Ga0.1As/GaAs layer pairs, respectively. The inner cavity of the multi-diode cascade VCSEL contains three active pn-junctions in series, each of which comprises three undoped 8 nm thick In0.2Ga0.8As quantum wells separated by 8 nm thick GaAs barriers. The active regions are coupled by two highly doped GaAs Esaki junctions of 21 nm thickness each to realize low resistance quasi-Ohmic inter-contacts for carrier recycling as schematically shown in Fig. 2. Thus, an injected electron can theoretically generate a new photon in each additional active region of the multi-diode cascade VCSEL, exhibiting a differential quantum
efficiency well exceeding unity. Moreover, the reverse biased Esaki junctions are placed in the nodes of the standing wave pattern to reduce free-carrier absorption. For the p- and n-type doping we use C and Si, respectively. Current confinement is achieved by mesa etching and subsequent homogeneous selective oxidation of three 30 nm AlAs layers incorporated above each active region. Thus, it is possible to reduce current spreading in the cavity that is an important issue for the improvement of cascade VCSEL performance [5]. Finally, a ring contact deposited on the mesa allows for top surface emission.

3. Esaki Junction

The performance of cascade VCSELs essentially depend on the implementation of low resistance tunnel junctions to minimize additional device heating. However, the realization is dominated by the n-type doping compensation effect in GaAs. With increasing n-dopant species concentration, eventually the dopant begins to substitute on the acceptor sites limiting the maximum donor incorporation. Our typical GaAs Esaki diode has an p- and n-type doping level of $1 \times 10^{20} \text{ cm}^{-3}$ and $2.5 \times 10^{19} \text{ cm}^{-3}$, respectively. The minimum zero-bias resistance is about $2.5 \times 10^{-4} \Omega \text{ cm}^{2}$, determined by a four-terminal measurement including contact and substrate resistivity.

4. Multi-Diode Cascade VCSEL

Fig. 3 illustrates the CW, room temperature output characteristics of a fabricated multi-diode cascade VCSEL with three oxide apertures of approximately $9 \mu \text{m}$ in diameter. The device can be driven far above roll-over without damaging and shows no saturable
absorber behavior as one might expect for a none homogenous current pumping profile between the active regions. At threshold, the emission wavelength is located at 980 nm with a current of 1.5 mA. The threshold voltage of 5 V is about 1.2 V higher than three times the bandgap voltage, indicating a successful implementation of low resistance Esaki junctions. Maximum output power of about 7.2 mW is obtained at a driving current of 9.2 mA. The observed differential quantum efficiency of 130% also confirms the successful realization of the cascade concept. For the wallplug efficiency we obtain a maximum value of about 16% at a current of 4.5 mA. The continuous wave spectrum for a driving current of 2.5 mA is displayed in Fig. 4. It shows strong multi-mode emission due to an increase in the optical guiding introduced by the additional oxide apertures.

5. Conclusion

We have demonstrated the first CW operating multi-diode cascade VCSEL at room temperature with a differential quantum efficiency well exceeding unity. The measurement results clearly demonstrate the successful implementation of low resistance Esaki junctions in the cavity for carrier recycling. Further work will include optimizing the Esaki junction and the cascade device structure but also the investigation of the modulation and noise properties of cascade VCSELs.

References


