

**CW-Operation of a Diode Cascade InGaAs Quantum Well VCSEL**

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A diode cascade vertical cavity surface emitting laser with two active pn-junctions connected in series is demonstrated, operating in cw mode up to 175 K. Differential quantum efficiency clearly exceeds 100 % and a maximum output power of 40 mW is obtained.

1. Introduction

Vertical cavity surface emitting laser diodes (VCSELs) of low threshold current below 100 µA [1], high wallplug efficiency above 50 % [P-35], and high-speed modulation capabilities [2] have been reported in the InGaAs-GaAs or GaAs-AlGaAs material systems mainly for optical interconnect applications. On the other hand, in external cavity configurations or in cases where high quality mirrors are not available, the extremely low roundtrip gain of electrically pumped VCSELs is a distinct disadvantage. Periodic gain structures [3] or lasers with two active layers [4] have been proposed to overcome this problem, but could be demonstrated with only limited success. In the present study we investigate diode cascade structures containing two active multiple quantum well layers connected by a modulation doped backward tunnel diode. This approach of applying several diodes in series may potentially lead to a threshold current close to the transparency current and provide high differential gain but requires an enlarged operating voltage depending on the number of pn-junctions employed.

2. Device Structure

A schematic of the MBE grown diode cascade VCSEL is shown in Fig. 1. The p- and n-type mirrors consist of conventional epitaxial AlGaAs-GaAs Bragg reflectors. The active region contains two pn-junctions in series, each of which comprises three undoped 8 nm thick In$_{0.2}$Ga$_{0.8}$As quantum wells (QWs) separated by 10 nm thick GaAs barriers and embedded in Al$_{0.4}$Ga$_{0.6}$As claddings. The pn-pn-structure requires a backward driven pn-diode with reasonably low voltages which is realized as a tunneling junction using high doping concentrations of $n = 5 \cdot 10^{18}$ cm$^{-3}$ (Si) and $p = 5 \cdot 10^{19}$ cm$^{-3}$ (C) within 10 nm thick AlGaAs layers. As indicated in Fig. 1, the active quantum wells are placed in antinodes of the standing wave pattern, whereas the reverse biased junction is located in the vicinity of a field null to reduce free-carrier absorption. Current confinement is achieved by wet
Fig. 1. Structure of a diode cascade VCSEL. The active layer consists of two sets each with 3 In$_{0.2}$Ga$_{0.8}$As QWs. The backward diode between the InGaAs stacks is placed in the node of the standing wave pattern to reduce absorption.

chemical mesa etching and subsequent selective oxidation of a 30 nm thin AlAs layer incorporated in the first Bragg pair above the active region. A ring contact deposited on the mesa allows for top surface emission.

3. Operation Characteristics

The output power and voltage versus current characteristics in Fig. 2 are measured for a diode cascade VCSEL with 16 µm oxide aperture at a heat sink temperature of 95 K.

Fig. 2. CW-output characteristics of a diode cascade VCSEL with an oxide aperture of 16 µm. The inset shows the emission spectrum of the device.
where the highest differential quantum efficiency of 1.2 is observed. Cascaded photon generation in the two pn-junctions is responsible for the differential quantum efficiency larger than 100 %. For a current of 43 mA the output power reaches 40 mW. The threshold voltage of about 7 V is still large compared to twice the bandgap voltage and is to be attributed to the non-negligible breakdown voltage of the backward driven tunnel diode. As depicted in the inset, the emission is centered at 953 nm wavelength and has a broad linewidth of about 1 nm. Fig. 3 shows the temperature dependence of the emission wavelength, which is given by the cavity resonance, leading to a shift of 0.084 nm/K similar to conventional VCSELs. Temperature dependent threshold current is also indicated in Fig. 3. A minimum threshold current of less than 9 mA is found at a heat sink temperature of about 150 K, when the gain peak of the QWs is aligned to the cavity resonance at 952 nm wavelength. The relatively large threshold current density of 4.5 kA/cm² might result from absorption in the highly doped backward junction as well as insufficient pumping of the QW stack near the substrate due to current spreading. Diode cascade VCSELs of smaller or larger active diameters show reduced maximum operating temperatures due to high voltages combined with increased resistances and current densities or operating currents, respectively.

The far field of the 16 µm diameter diode cascade VCSEL is illustrated in Fig. 4 and shows a full width at half maximum of only 6.2° compared to 9.7° of a conventional MQW VCSEL of identical aperture size. Near field broadening resulting from current distribution might be responsible for this effect, but further investigations are required for clarification.
4. Summary

In conclusion, we have proposed and fabricated first diode cascade quantum well VCSELs. Although the devices still suffer from a high voltage drop and absorption at the backward diode, a cw output power of 40 mW as well as a differential quantum efficiency of 120 % is achieved, indicating successful implementation of the cascade concept. Future work should be devoted to the optimization of the backward junction and a better current confinement for the QW active layers.

References


