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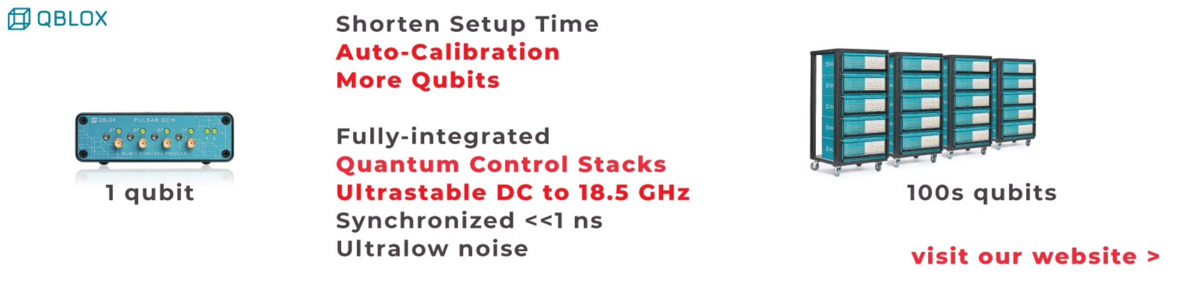

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High-power semiconductor disk laser based on InAs/GaAs submonolayer quantum dots

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An optically pumped semiconductor disk laser using submonolayer quantum dots (SML QDs) as gain medium is demonstrated. High-power operation is achieved with stacked InAs/GaAs SML QDs grown by metal-organic vapor-phase epitaxy. Each SML-QD layer is formed from tenfold alternate depositions of nominally 0.5 ML InAs and 2.3 ML GaAs. Resonant periodic gain from a 13-fold nonuniform stack design of SML QDs allows to produce 1.4 W cw at 1034 nm. The disk laser demonstrates the promising potential of SML-QD structures combining properties of QD and quantum-well gain media for high-power applications. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2898165]

Semiconductor disk lasers (SDLs) represent promising sources for optical systems which require high power combined with excellent beam quality such as laser-projection displays or optical storage devices.[1] SDL-based intracavity frequency upconversion has already resulted in impressive output power sufficient for practical systems.[2] The demonstrated SDLs, to date, are based on quantum wells (QWs).[1–5] Localization of charge carriers in gain media using quantum dots (QDs) with high areal density has been employed in the last decade to fabricate novel or dramatically improved lasers.[6] The submonolayer (SML) growth mode of QDs represents an attractive solution for fabricating QDs with an ultrahigh density to achieve increased gain.[7,8] They benefit from high excitonic gain, a characteristic feature of zero-dimensional structures,[9] combined with the high modal gain of QWs. The extended emission-wavelength tuning ability and improved temperature stability of QDs, as compared to QWs, suggest promising performance for high-power SDLs. QDs grown using SML deposition also present a basis for ultrahigh-speed vertical-cavity surface-emitting lasers.[10] These devices show very good temperature stability as well as high gain and are based on SML QDs (Ref. 11) grown with the same SML deposition parameters as used for the present SML SDL devices. Further investigations on specific SML QD properties for SDLs are part of ongoing work and will be published elsewhere. We present here SDLs fabricated using SML QDs for emission near 1040 nm, an appropriate wavelength to provide frequency-doubled green for laser display systems. A high-power 1.4 W SDL is demonstrated based on a periodic gain structure of stacked InAs/GaAs SML-QD layers.

The growth is performed on undoped (1 0 0) GaAs substrates using metal-organic vapor-phase epitaxy with alternative precursors.[12] SML QDs are grown at 500 °C, each SML-QD layer consisting of a tenfold cycled alternate deposition of nominally 0.5 ML InAs and 2.3 ML GaAs [see Fig. 1(c)]. The amount of InAs in each individual deposition is below the critical thickness for three-dimensional QD formation in the Stranski–Krastanow (SK) growth mode. The first InAs SML deposition causes initial island formation on the surface.[13] After rapid coverage of these islands with a few GaAs monolayers, the locations of islands nucleating in the next InAs SML are controlled by the nonuniform strain distribution of the buried InAs islands.[14,15] A low V/III ratio of 2 to 3 is applied during SML-QD growth to reduce In/Ga interdiffusion. Similar growth conditions have recently been used for fabrication of highly efficient SK-QD lasers.[16] The SML-QD layer formed from the cycled InAs/GaAs depositions is covered by additional 2 nm GaAs before raising the temperature to 595 °C to improve the quality of the GaAs spacer. Before the deposition of the next SML-QD layer, the temperature is decreased again to 500 °C. The entire gain medium comprises of 13 SML-QD layers, placed at the an-

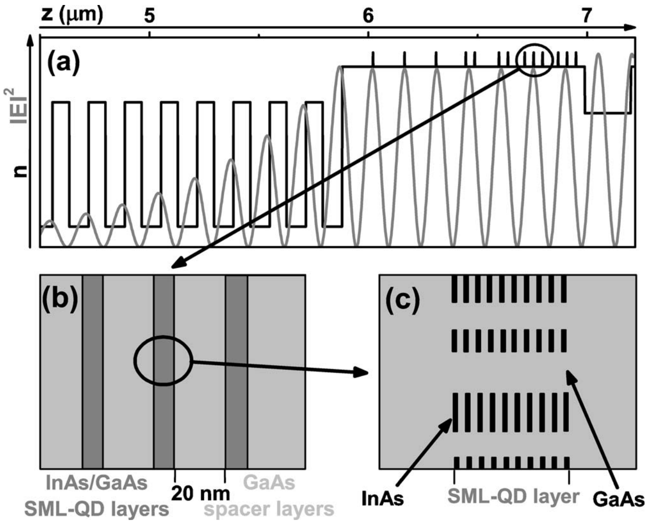

FIG. 1. Schematic of the SML-QD SDL. (a) Refractive index profile (black) and calculated optical field (gray) as a function of vertical position z. Only a part of the Bragg mirror is shown. (b) Group of threefold stacked InAs/GaAs SML-QD layers. (c) Expanded sketch of a single SML-QD layer showing InAs SML depositions in GaAs.

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tinodes of the standing optical wave in the SDL [Fig. 1(a)]. Using materials parameters given in Ref. 17, the SML-QD layers are arranged in a nonuniform design calculated for normal surface emission using the transfer-matrix method. To efficiently exploit the exponentially decreasing intensity of the pump light, two groups of three SML-QD layers are placed in the two topmost antinodes and groups of two SML-QD layers in each of the following two antinodes. The nominal thickness of the GaAs spacers between SML-QD layers within the same group is set to 20 nm [Fig. 1(b)]. Each of the last three antinodes closest to the distributed Bragg reflector (DBR) contains a single SML-QD layer.

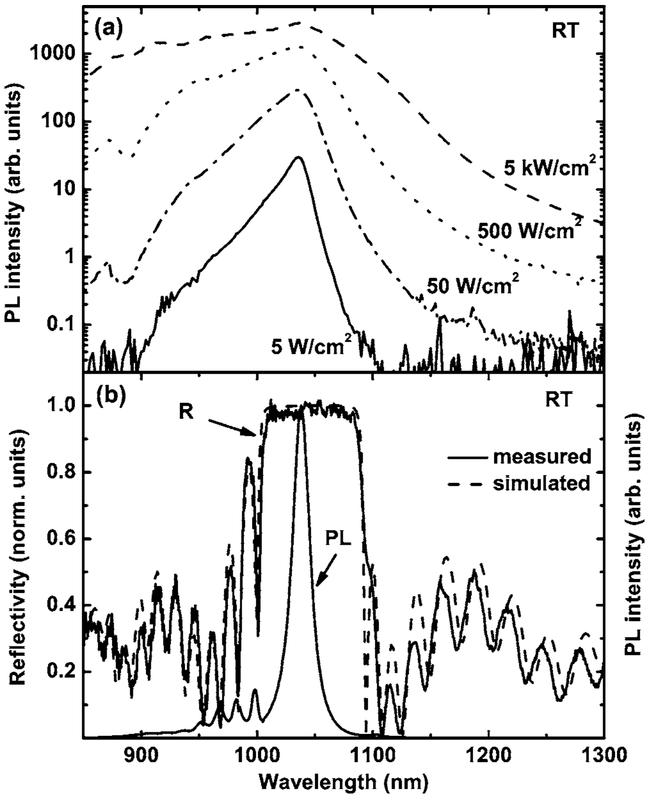

FIG. 2. (a) PL of a single SML structure in a QD test sample without DBR at different excitation densities. (b) Normalized surface-emitting PL, measured reflectivity, and simulated reflectivity, of the SML-QD SDL structure.

Growth parameters are optimized utilizing photoluminescence (PL) of SML QDs excited by a frequency-doubled Nd:YAG (yttrium aluminum garnet) laser at 532 nm. The optimization aims at narrow spacers within a group of SML-QD layers without structural degradation ensuring intense luminescence at the target wavelength. PL test structures comprised either a single SML-QD layer or stacked SML-QD layers embedded in a 300 nm thick GaAs matrix, sandwiched between two 45 nm thick AlGaAs charge-carrier diffusion barriers. All structures are grown on a 300 nm thick GaAs buffer layer.

The DBR is grown at 680 °C and has 35.5 pairs of alternating $\lambda/4$ layers of Al$_{0.98}$Ga$_{0.02}$As and Al$_{0.2}$Ga$_{0.8}$As. The whole structure is grown without strain-compensating layers. The barriers between the SML QDs contain solely GaAs as pump absorbing material. Recombination of photoexcited carriers at the surface is prevented by an Al$_{0.3}$Ga$_{0.7}$GaAs layer capped with 10 nm GaAs on top of the structure grown at 680 °C.

To assess the characteristics of the SML-QD SDL room temperature PL and surface reflectivity are measured. The PL shown in Fig. 2(b) is recorded normal to the sample surface at a high pump level of 5 kW/cm^2. It is a convolution of the DBR reflectivity, the subcavity formed by the DBR and the semiconductor/air interface, and the PL of the SML QDs is shown in Fig. 2(a). The surface PL features a broadening at high excitation density basically due to state filling effects. The intense PL maximum coincides with the PL maximum of SML-QD test structures without DBR mirror.

A 300 μm thick natural diamond heat spreader is liquid capillary bonded on a 2.5×2.5 mm^2 wafer piece. Mounting on a water-cooled (15 °C) copper heat sink is realized by clamping the bonded wafer between two copper plates. The topmost plate includes a small circular aperture for pump and signal light. An 808 nm fiber-coupled diode laser used for pumping the SDL structure produces up to 20 W of power launched at an incident angle of 35° to the surface normal. The pump light is focused to a 180 μm diameter spot that matches accurately the size of the cavity mode. The V-shaped cavity consists of a curved mirror with 200 mm radius of curvature, a plane output-coupler mirror, and the QD gain mirror.

The lasing spectrum given in Fig. 3 (inset) shows fringes due to the etalon effect of the diamond intracavity heat spreader. The central lasing wavelength of 1034 nm represents an optimum to achieve a large color gamut for frequency-doubled green in red-green-blue displays. Using 1% outcoupling, a maximum cw output power of 1.4 W almost without thermal rollover is observed for a pump power of 20 W (see Fig. 3). The corresponding optical-to-optical conversion efficiency is 7% with 12.4% slope efficiency. These values approach well those of excellent QW-based devices.[18]

The spatial intensity profile of the laser beam recorded at 570 mW output power with a charge-coupled device camera is shown in Fig. 4. The profiles given for two orthogonal directions are close to actual Gaussian distributions, indicating the nearly diffraction-limited nature of the radiation and proving TEM$_{00}$ emission of the SDL.

To conclude, operation of an optically pumped semiconductor disk laser based on a 13-fold nonuniform SML quantum dot stack as gain medium is demonstrated. With these

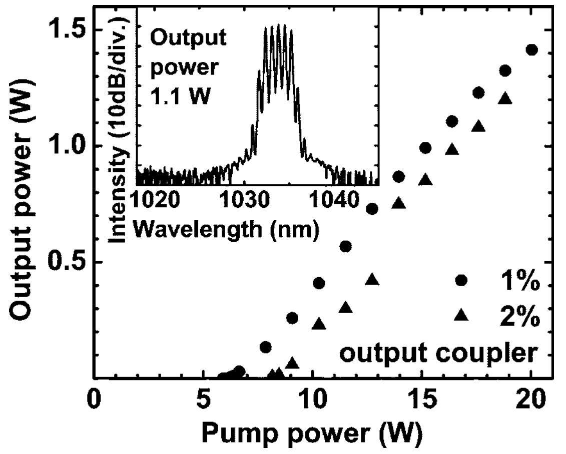

FIG. 3. Light output characteristics with different output couplers of the SDL cavity comprising a SML QD gain medium. Inset: laser spectrum recorded at 1.1 W output power.

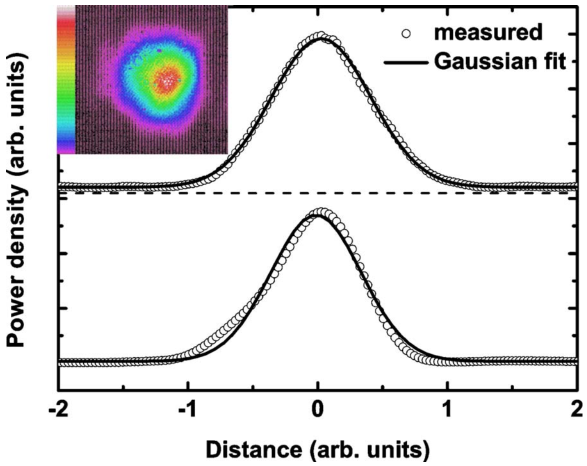

FIG. 4. (Color online) Spatial intensity profile of the output beam with Gaussian fit for two orthogonal directions. Upper and lower spectra refer to vertical and horizontal directions, respectively.

devices, cw optical output power of 1.4 W at 1034 nm is achieved, demonstrating the promising potential of this type of quantum dots for high-power applications. Due to the broader gain spectrum of the SML QDs, a larger tuning range and higher temperature stability are expected for such devices.

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