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Temperature-dependent characteristics of 1.3 μm InAs/InGaAs/GaAs quantum dot ring lasers

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The temperature characteristics of ring lasers with a diameter of 480 μm of an original design with an active region based on 10 layers of InAs/InGaAs/GaAs quantum dots are studied. The lasers demonstrated a low threshold current density (200 A/cm^2 at 20°C), the characteristic temperature of the threshold current in the range of 20−100°C was 68 K, the maximum lasing temperature was as high as 130°C. These values are only slightly inferior to the parameters of the edge-emitting lasers fabricated from the same epitaxial wafer.

Keywords: semiconductor ring lasers, InAs/GaAs quantum dots, optical waveguide, temperature characteristics.

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Semiconductor lasers with the following two types of cavities and waveguides are the most widely used: edge-emitting stripe lasers and vertical-cavity surface-emitting lasers. Other less widespread designs of semiconductor lasers tailored for various specific applications have also been developed. Among these are, e.g., ring lasers with mode-locked operation that serve as sources of stable sequences of short optical pulses (several picoseconds in length) with a repetition rate of several tens of gigahertz, which is set by the cavity length. Such emitters have promising applications in optical communications, clock pulse generation, optical probing, biological and medical research, microwave photonics, etc. Their key feature is directly related to the technological capacity (specifically, the photolithography equipment capacity) to reproduce cavities of a precise (down to ∼ 1 μm) length and fabricate devices with a specific predefined pulse repetition rate. This is what distinguishes ring lasers from standard stripe ones with a cavity formed by cleaving a semiconductor crystal accurately to within several tens of micrometers: with this processing method, the repetition rates of optical pulses vary widely from one stripe laser to the other.

The ever-growing use of optical-fiber communications was the motivation behind studies of ring lasers on InP substrates operating in the spectral range around 1.55 μm [1–4]. Lasers based on quantum wells of the InP material system have a drawback in that a complex laser structure regrowth process is involved in their fabrication [5]; in addition, their parameters depend strongly on temperature (due to the small band offsets typical of this material system). An alternative option is the use of lasers based on GaAs substrates with In(Ga)As/GaAs quantum dots (QDs), which have a number of significant advantages: low threshold current density, high temperature stability of parameters, small line broadening factor (alpha factor), and weak influence of surface recombination and growth defects on the characteristics of devices. Owing to their high temperature stability, QD lasers may be used without a thermal stabilization system. A data transfer rate of 10.3 Gb/s at a fixed injection current and temperatures up to 85°C was achieved in [6]. The highest temperature of continuous-wave (CW) operation of a 1.3 μm QD laser reported in literature was 220°C [7]. The advantages of edge-emitting QD lasers stem from the fundamental properties of their active region and should be retained in ring lasers.

We have already proposed and implemented an original design of semiconductor ring lasers based on InAs/InGaAs/GaAs QDs [8]. The strengths of this design lie in the simplicity of the post-growth technology, which does not involve regrowth or planarization, and the potential to fabricate multisection lasers (e.g., for the purposes of generation of short pulses in mode-locked operation). Lasers have demonstrated a low threshold current density of 150 A/cm^2 and an output power of 45 mW in the CW mode. In the present study, we examine the temperature characteristics of these ring lasers.

The epitaxial structure was was grown by molecular beam epitaxy on an *n*-GaAs(100) substrate. The active region was formed from ten layers of InAs/InGaAs/GaAs QDs emitting in the optical range of 1.3 μm and separated by GaAs spacers 36 nm in thickness. The growth method used for QD fabrication was as follows: the initial dots,

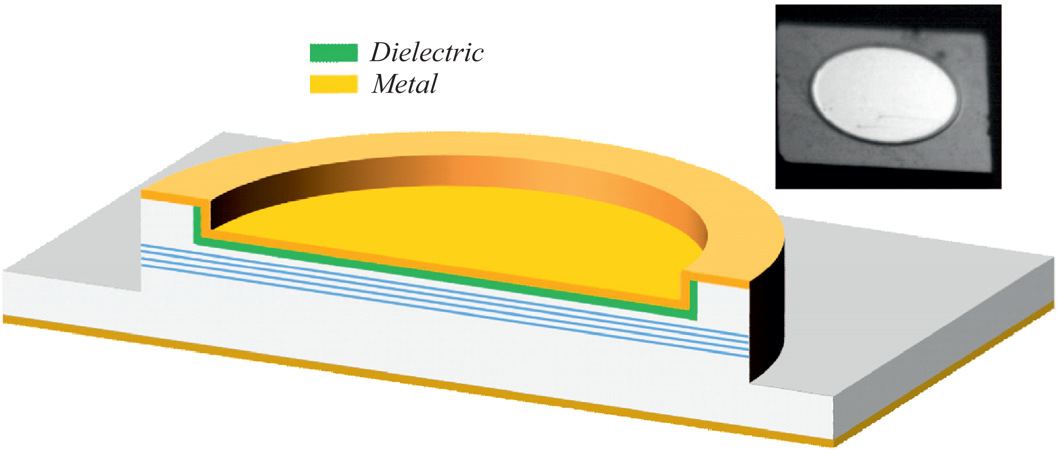

Figure 1. Schematic diagram (not to scale) of the cross section and photographic image (inset) of the ring laser.

which were prepared by InAs deposition (0.8 nm) in the Stranski–Krastanov growth mode, were coated with an $In_{0.15}Ga_{0.75}As$ layer of an average thickness of 5 nm [9]. The active region was positioned at the center of an undoped GaAs waveguide with a thickness of 0.4 μm located between $Al_{0.25}Ga_{0.75}As$ *n*- and *p*-claddings. The design of the ring laser (Fig. 1) and its primary parameters were detailed in [8]. The lateral asymmetric waveguide is a distinguishing feature of this design: on the outside of the ring, the structure is etched to a considerable depth of 5 μm, while the inner waveguide part is etched just to the depth of the contact layer and (partially) the top cladding. The width of the ring waveguide is 10 μm, and the ring diameter is 480 μm (the ring perimeter is 1.5 mm). The inner part of the ring is coated with a dielectric Si_3N_4 layer, which makes it possible to deposit a solid metallic circular *p*-contact onto the entire top surface of the laser. The bottom substrate surface serves as an *n*-contact. This design allows one to divide the ring into sections with separate metallic contacts at the post-growth processing stage. Depending on the polarity of the applied bias, these sections may be absorbing or amplifying, which is needed for mode-locked operation [1]. Multisection lasers of this type are mounted on a heatsink p-side up and operate under DC pumping of the amplifying section. This is the reason why thermal operating conditions are rather severe. Surface recombination on side walls formed by plasma-chemical etching may also contribute to the temperature dependence of characteristics of ring lasers. In order to estimate the influence of this effect and other design features of the ring laser on the threshold current density and its temperature sensitivity, standard edge-emitting lasers 100 μm in width were fabricated from the same epitaxial structure.

Ring and edge-emitting lasers were mounted to copper heatsink with indium solder. Measurements for ring lasers mounted p-side up were performed under DC pumping by a stabilized Keithley 2401 sourcemeter within the temperature range of 20–150°C. Their radiation was collected by a Mitutoyo M Plan Apo NIR objective with a magnification power of 50x and sent via optical fiber to a Yokogawa AQ6370C optical spectrum analyzer. The radiation of edge-emitting lasers, which were mounted p-side down, was measured under pulsed current pumping. This helped prevent overheating of the active region and provided an opportunity to examine the near-limit temperature sensitivity of the threshold current density. The radiation of these lasers was collected by a lens and detected using a monochromator and an InGaAs photodetector.

Figure 2, *a* shows the emission spectra of the ring laser 480 μm in diameter recorded within a wide wavelength range at different temperatures. A broad spontaneous emission omitting band, which is typical of self-organized InAs/InGaAs/GaAs QDs [10], is seen in the spectra: the long-wave maximum at 1265 nm corresponds to the fundamental optical transition of QDs, while the shorter-wave peak at 1175 nm represents the first excited optical transition. These spontaneous emission peaks are several tens of nanometers wide. As the pumping current increases, a narrow lasing line, which corresponds to one of the whispering-gallery cavity modes, emerges on the broad ground-state emission peak (Fig. 2, *b*). Lasing s observed up to 130°C.

The threshold current value was assumed to correspond to the characteristic kink in the dependence of the integrated whispering-gallery mode intensity on the pumping current (inset in Fig. 3). At room temperature, the threshold current density of ring lasers was 210 A/cm^2, while the value determined for edge-emitting lasers was slightly lower (160 A/cm^2). This subtle difference may be attributed to a more significant current spreading in ring lasers, the contribution of surface recombination on the side wall of the ring laser formed by plasma-chemical etching, and the fact that measurements for edge-emitting lasers were performed under pulsed pumping.

The temperature dependences of the threshold current of ring and edge-emitting lasers in the 20–100°C range are

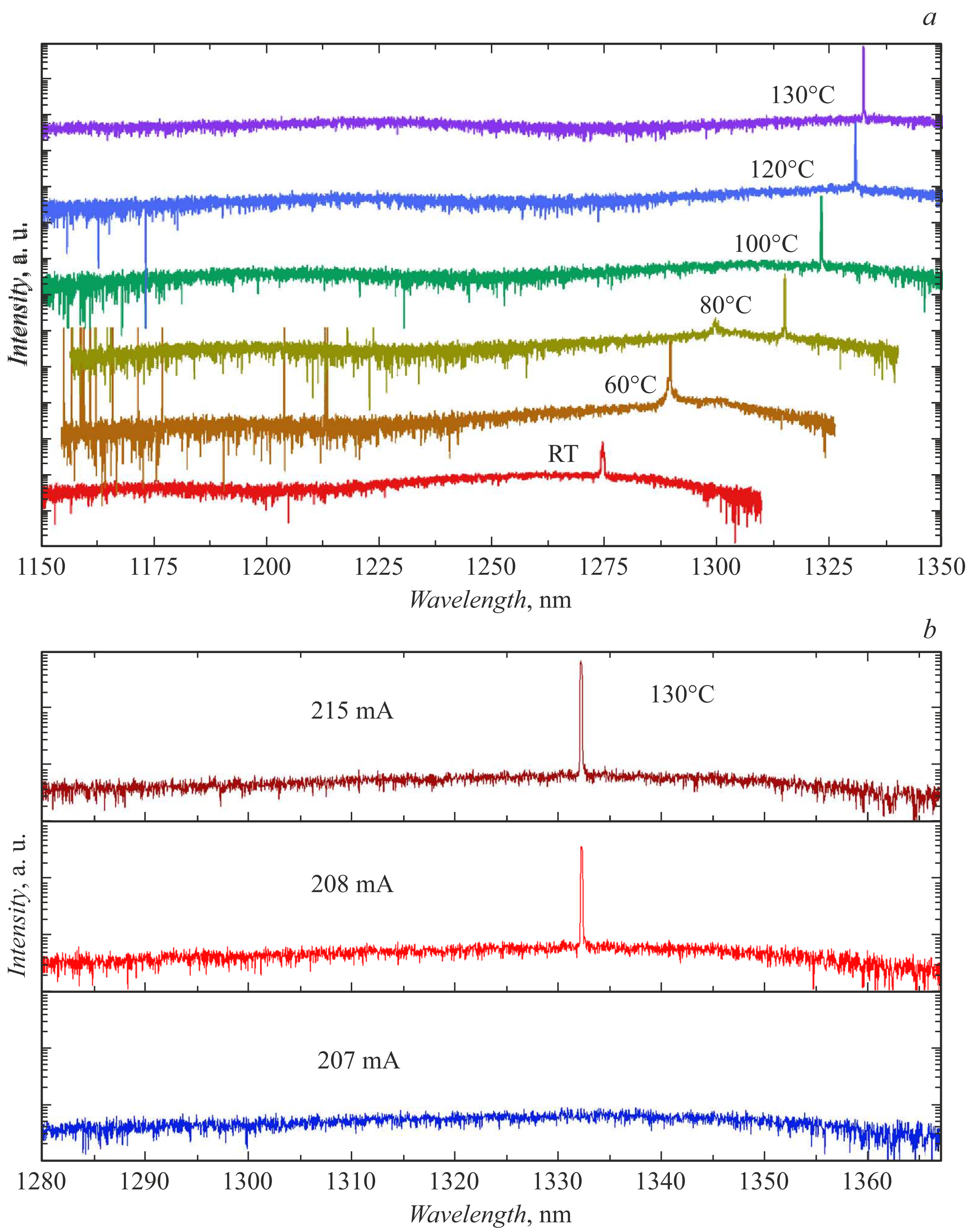

Figure 2. Lasing spectra at different temperatures (a) and different currents at 130°C (b).

approximated well by the following expression: $\exp(T/T_0)$, where T_0 is characteristic temperature. The values of T_0 were found to be equal to 68 and 75 K for ring and edge-emitting lasers, respectively. The threshold current in the ring laser grows rapidly as the temperature increases to 130°C. This is apparently attributable to the carrier escape from from QDs into the matrix and the wetting layer and their subsequent radiative and non-radiative recombination (including recombination on the side surface of the device). The temperature dependence of the threshold current density of the ring laser grows faster due to self-heating of the active region, which is induced by the fact that the laser operates under continuous pumping and is mounted on a heatsink p-side up.

Thus, it was demonstrated that our original design of ring injection lasers with an active region based on InAs/InGaAs/GaAs quantum dots does indeed achieve lasing under CW pumping at temperatures up to 130°C. The characteristic temperature of the threshold current for ring lasers is only slightly lower than the one for stripe lasers fabricated from the same epitaxial structure. Therefore, the studied ring lasers hold promise for application in various optical systems operating without temperature stabilization.

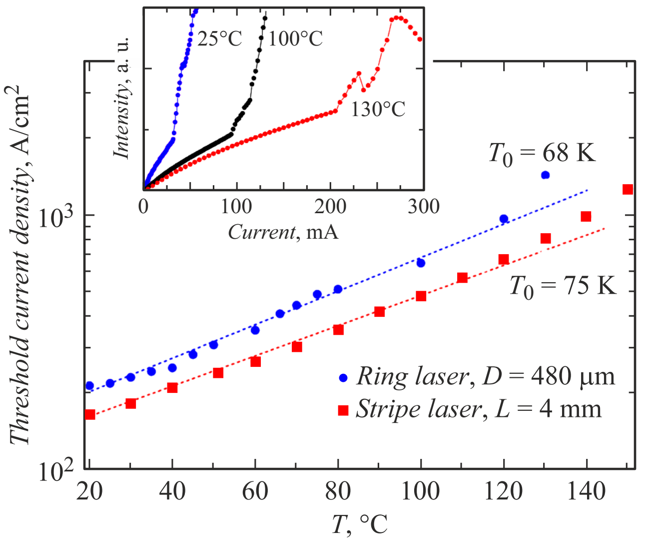

Figure 3. Temperature dependence of the threshold current for ring and edge-emitting lasers. The current dependences of the integrated intensity of the dominant lasing line measured at three different temperatures are shown in the inset.

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Conflict of interest

The authors declare that they have no conflict of interest.

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