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Molecular beam epitaxial growth of InAs quantum dots on GaAs for high characteristics temperature lasers

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Abstract: GaAs-based 1.3 μm InAs quantum dot laser have been grown by MBE system. Under the optimized InAs quantum dots growth temperature of 520 ℃, and the methods of Be-doping in the active region are adopted for better device performance. With a ridge width of 100 μm and cavity length of 2 mm, the maximum output power of single facet without coating has reached up to 1008 mW under continuous wave (CW) operation at room temperature, and the threshold current density is 110 A/cm^2. The QD lasers can still operate at continuous waves (CW) up to 80 ℃, and the characteristic temperature below 50 ℃ is as high as 405 K.

Key words: quantum dot laser, molecular beam epitaxy, characteristics temperature, mid-infrared

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利用分子束外延在GaAs基上生长高特征温度的InAs量子点激光器

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摘要:通过MBE外延系统生长了1.3 μm的GaAs基InAs量子点激光器.为了获得更好的器件性能,InAs量子点的最优生长温度被标定为520 ℃,并且在有源区中引入Be掺杂.制备了脊宽100 μm,腔长2 mm的激光器单管器件,在未镀膜的情况下,达到了峰值功率1.008 W的室温连续工作,阈值电流密度为110 A/cm^{-2},在80℃下仍然可以实现连续工作,在50 ℃以下范围内,特征温度达到405 K.

关 键 词:量子点激光器;分子束外延;特征温度;中红外

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Introduction

In recent years, 1.3 μm quantum dot (QD) laser has become an important light source for optical communication.[1-3] Compared with traditional quantum well laser, quantum dot laser have more advantages, such as lower threshold current, lower temperature dependence and higher WPE.[4] Continuous high-power operation will cause obvious laser heating, which will worsen the performance of the device. Thus, the thermal effect has garnered much attention and needs to be further optimized[5-6]. The effect of thermal efficiency on the performance of quantum dot laser has made people pay special attention to taking various methods to eliminate the heat generation or reduce the sensitivity of devices to temperature when improving the performance of quantum dot laser.[7-8] The device characteristics of semiconductor quantum dot laser have been improved with progress in active layer structures.[9] The growth of active layer (InAs QDs on GaAs) has a tendency to form islands due to the large lattice mismatch, almost 7.16%, which results in Stranski-Krastanow (S-K) growth mode, epitaxial growth changes from 2D to 3D, which is suitable here for the proposed heterojunction material system with a mismatch in lattice constants but a low interfacial energy.[10] The growth quality (density and size uniformity) of QDs is a vital index of the growth quality of active region.[11] To obtain high quality quantum dots, various researches have been carried out to optimize the parameters of quantum dots[12-13]. As we know, the characteristic temperature of the semiconductor laser is the core physical parameter to measure the temperature characteristics.[14] The characteristic temperature of 1.3 μm quantum dot laser reported by Kim of Stanford University has reached 210 K. In their research, the active region of the laser is undoped.[15] However, the latest research indicates that p-doping in the active region is beneficial to further improve the temperature characteristics and the threshold current of the device.[16]

The device characteristics of quantum dot laser are mainly limited by the growth conditions of the active region. To obtain better performance quantum dot laser, the growth temperature of the active region was optimized, and Be-doping in the active region was introduced for better temperature characteristics. We will show the fabrication of high characteristic temperature with low threshold current density single emitter diode laser device with 100 μm-wide and 2 mm-long cavity. The peak power of quantum dot laser reached 1008 mW. The threshold current density is 110 A/cm^2, and the characteristic temperature below 50 ℃ is 405 K by fitting the curve between threshold current and temperature.

1 Structure characterization and fabrication

The quantum dot laser structure shown in the Fig. 1 was grown on N-type GaAs (100) substrates exploiting a Gen 930 solid-source Molecular beam epitaxy (MBE) system from Veeco Instruments equipped with in-situ reflective high-energy electron diffractometer (RHEED) calibrating the growth temperature by the GaAs reconstruction.[17] A 500 nm Si-doped buffer layer was firstly deposited on a 2-inch N-type GaAs (100) substrate for better flatness of the substrate. The active region consists of five loops of the QDs layers, and each QDs layers contains 1.5 nm Be-doping (p: 5e17) GaAs and 2.5 monolayer (ML) InAs capped by a 5nm $In_{0.15}Ga_{0.85}As$ strain-reducing layer and a 40 nm GaAs layer. Two 70 nm thick non-doped GaAs waveguide layers, which surround the active region, were chosen to improve the optical confinement. The 0.4 μm waveguide core that includes the active region and the waveguide layer is sandwiched between two 1.4 μm $Al_{0.45}Ga_{0.55}As$ cladding layers. The n-cladding layer is Si doped to 2×10^{18} cm^{-3}, and the p-cladding layer is Be doped to 2×10^{18} cm^{-3}. The whole structure was finally capped by 200 nm GaAs ohmic contact layer which is Be doped to 3×10^{19} cm^{-3}.

The growth temperature of the QD is the vital parameter in the MBE epitaxy of the laser. At lower temperature, the density of quantum dots is the highest, but the uniformity is not enough, and it is easy to form large dot defects. The uniformity of quantum dots is better at higher growth temperature, but the high growth temperature will lead to the desorption of InAs quantum dots, which will lead to the decrease of the quantum dots density. To find the optimized growth temperature of the QDs, photoluminescence (PL) spectrum and atomic force microscope (AFM) were carried out on three QDs samples with the growth temperature of 510 ℃, 520 ℃ and 530 ℃. All the PL spectra shown in Fig. 2 were obtained with a Fourier transform infrared spectroscopy (FTIR) by detecting the PL signals excited by a 500 mW 628 nm diode laser, and it is obvious that the sample grown at 520 ℃ has the best optical quality among the three samples. As indicated in Fig. 3, the sample grown at 510 ℃ has several large dots defects which will deteriorate the performance of the device, and the density of quantum dots of the sample grown at 530 ℃ is the lowest which led to lower optical quality. The growth temperature was finally optimized to 520 ℃, and the full width at half maximum (FWHM) is 35 nm and the density of the QDs is 5.0×10^{10} cm^{-2}.

The grown epitaxial wafers were processed into diode laser with a ridge waveguide of 100 μm wide, 2 mm long and 1.5 μm deep using contact optical lithography

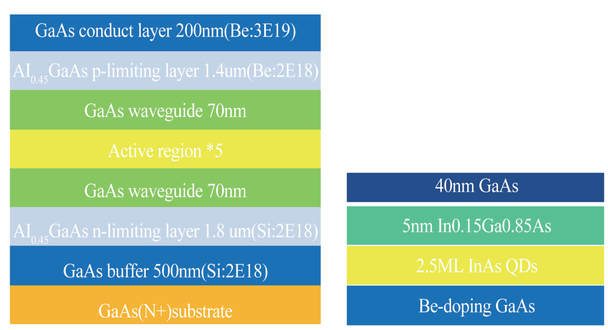

Fig. 1 The structure of the QD laser and the structure of the active region
图1 量子点激光器全结构示意图与有源区结构图

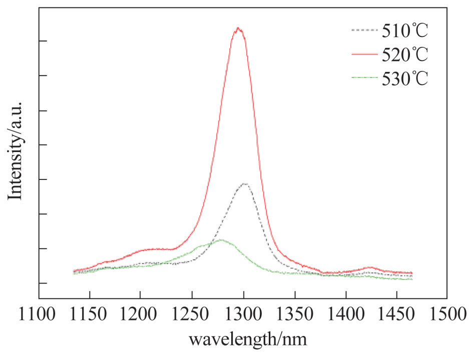

Fig. 2 PL spectrum of the three QDs samples with growth temperature of 510℃, 520℃ and 530℃
图2 量子点材料在不同生长温度(510℃,520℃ and 530℃)下的光致发光光谱(PL)

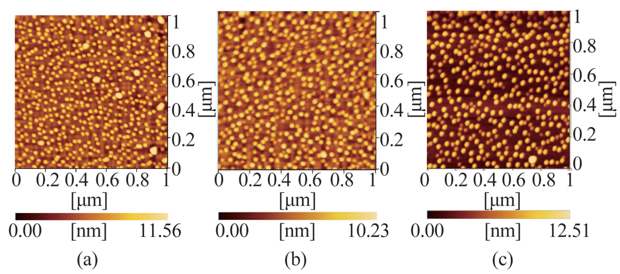

Fig.3 Atomic force microscope (AFM) image of the three QDs samples (a) 510 ℃, (b) 520 ℃, and (c) 530 ℃)
图3 量子点材料在不同生长温度下的原子力显微镜(AFM)图(a)510 ℃,(b)520 ℃,(c)530 ℃)

followed by inductively coupled plasma (ICP) dry etching. Then 90 μm wide, 1.9mm-long electrode aperture was open using ICP etching on the 200 nm SiO_2 insulation layer deposited by PECVD. After that, the p-side Ti/Pt/Au electrode was formed by magnetism sputter system. The n-side Ohm contacts were realized by fast-annealing the evaporated AuGeNi/Au film after the wafers were thinned to 150 μm. Finally, the wafers were cleaved into single emitter, and all the laser devices were mounted p-side down on copper heat sinks with Indium solder.

2 Laser performance and discussion

All the laser performance was measured without facet coating. The measurements of lasers output power were done by a pyroelectric detector and the emission spectra were scanned using a Fourier transform infrared spectroscopy (FTIR) system. The Continuous wave power-current-Voltage (*P-I-V*) characteristics and wall plug efficiency (WPE) at RT is shown in Fig. 4, and the maximal output power reaches 1 008 mW at the injection current of 3.6 A, then as the current increased further the output power was limited for the reason of heat accumulation. The threshold current density is 110 A/cm^2 and the WPE is 29%. The central wavelength of the lasing spectrum is 1.3 μm shown in Fig. 5. Due to p-doping in the active region, the impurity atoms provide a lot of extra holes to fill the valence band energy level of the quantum dots, which makes the valence band energy level always in the state of filling. It is difficult for the ground state holes to escape from the heat, which improves the probability of the ground state carrier occupation of the valence band, and thus improves the characteristic temperature of the quantum dot laser. [18] To study the thermal stability of the device, the power-current curve was measured at 5 ~80 ℃ in Fig. 6. The QD laser device is still continuous-wave working at 80°C, and the threshold current is insensitive to temperature. The characteristic temperature of the device is 405 K by fitting the curve between threshold current and temperature, which is owing to the optimization of epitaxy and p-doping in the active region.

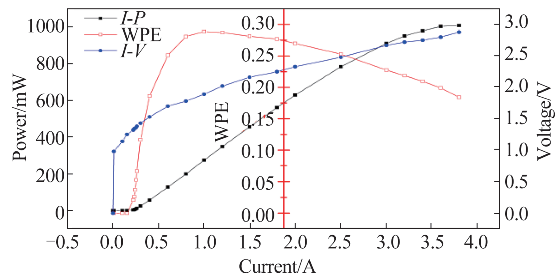

Fig. 4 *P-I-V* and WPE characteristics of the laser at CW mode
图4 激光器室温下连续工作模式下的功率-电流-电压关系和不同电流下的插头效率

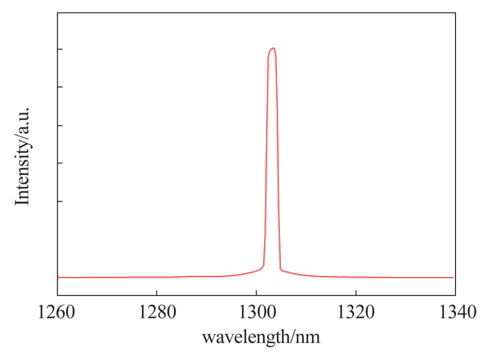

Fig. 5 Lasing spectrum at RT (The central wavelength is 1.3 μm)
图5 室温下的激光器的激射谱(峰值波长为1.3 μm)

3 Conclusion

In conclusion, we obtained 1.3 μm QD laser operating at room temperature with high characteristic temperature based on the optimization of the growth temperature and proper Be-doping in the active region. The uncoated facet single-emitter laser devices which had 100 μm-wide and 2 mm-long cavity with threshold current density of 110 A/cm^2 were fabricated. For each single quantum dots layer, the threshold current density is as low as 22 A/cm^2. The peak power of quantum dot laser reached 1008 mW at the injection current of 3.6 A. The highest continuous wave operating temperature is 80 ℃, and the characteristic temperature is 405 K by fitting the curve

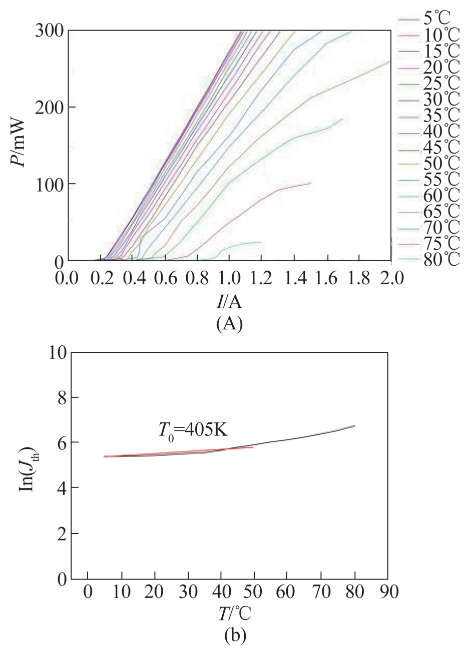

Fig. 6 The power-current (*P-I*) characteristics in different temperature (5~80℃) and the fitting curve between threshold current and temperature

图6 激光器在不同工作温度下(5~80℃)的功率-电流关系和阈值电流随温度变化的拟合曲线

between threshold current and temperature.

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