One-Dimensional InP-Based Photonic Crystal Quantum Cascade Laser Emitting at 5.36μm*

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Abstract: An InP-based one-dimensional photonic crystal quantum cascade laser is realized. With photo lithography instead of electron beam lithography and using inductively coupled plasma etching, four-period air-semiconductor couples are defined as Bragg reflectors at one end of the resonator. The spectral measurement at 80K shows the quasi-continuous-wave operation with the wavelength of 5.36μm for a 22μm-wide and 2mm-long epilayer-up bonded device.

Key words: quantum cascade laser; photonic crystal; quasi-continuous-wave
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1 Introduction

During the past few years, the performances of quantum cascade lasers (QCLs)[1] have been significantly improved. At present, room temperature (RT) continuous-wave (CW), high-power and low-threshold operations are not so hard to achieve[2~4]. To some extent, the QCLs have already been available in practical application. Recently, intense interest has arisen in photonic crystal (PhC) based on QCLs. Compared with normal short-wavelength lasers, QCLs, which emit in the mid- and far-infrared band, are more convenient in the fabrication of photonic crystals. Furthermore, the losses induced by the non-radiative recombination of electron-hole in PhC QCLs can be ignored due to the unipolarity of the QCLs. The first photonic crystal quantum cascade laser (PhC QCL) was demonstrated by Colombelli *et al*.[5] in the Bell laboratory in 2003. It was two-dimensional (2D), based on InP, and surface-emitted. Reference [6] reported the operation of an edge-emitting GaAs-based PhC QCLs at 120K, where the 2D photonic crystal forms a high-reflectivity mirror and waveguide. A similar but simplified manner to improve the reflectivity of the resonator is to define a one-dimensional (1D) photonic crystal with air-semiconductor pairs at the end of the resonators. In this way, Semmel *et al*. realized 1D edge emitting InP-based PhC QCLs[7]. Although some progress has been achieved in PhC QCLs, all these fabrications adopted metal as the mask and electron beam lithography to define the PhC patterns, which made them very difficult and complicated.

In this paper, we report the successful fabrication of 1D PhC QCLs with the popular photo lithography and mask of SiO_2. The high-quality air-semiconductor pairs are defined at one end of the resonator and the operation of the PhC laser is demonstrated.

2 Experimental results and discussion

The QCL structure is grown by Veeco GEN-II solid-source molecular beam epitaxy (MBE) on an n-doped ($n = 3 \times 10^{17} cm^{-3}$) InP substrate in a single growth step. The active region consists of a 30-period strain-compensated $In_{0.6}Ga_{0.4}As/In_{0.44}Al_{0.56}As$ well and barrier layers superlattice. The specific structure is identical to those reported in Ref. [8]. The active region is sandwiched between two 0.3μm-thick lightly doped InGaAs layers. The growth ends with a 2μm-thick lowly doped InAlAs cladding layer and a 0.5μm-thick highly doped InAlAs cap layer. The aggregate thickness of the structure grown on the substrate is about 4.63μm.

To attain the Bragg reflector, the thickness of every medium layer must satisfy:

$$d_i = (2N+1)\lambda/4n_i, \quad N = 0,1,2,\cdots \qquad (1)$$

Here, n_i is the refractive index of the medium layer and λ is the emission wavelength of the QCL, which has been measured as 5.36μm at 80K for a device with the same structure but with a normal ridge waveguide. With $N = 0$, the thickness of the air layer is chosen to be 1.34μm. Due to the diffractive effect

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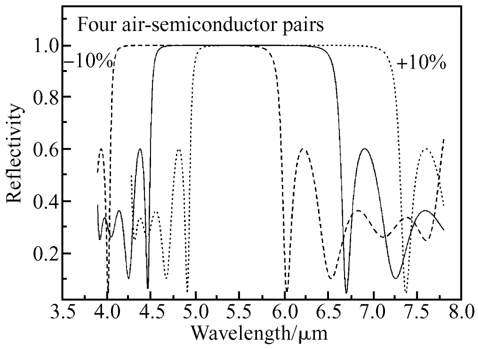

Fig. 1 Calculated reflectivity as a function of wavelength for the Bragg reflector made of four air-semiconductor pairs The conditions of ±10% differences from the designed thicknesses of air/semiconductor layer are also shown.

of photo lithography, the fabrication of the thin semiconductor layer brings many complexities to the pattern writing. So, the value of N is chosen to be 1 instead of 0, and with the general refractive index of 3.35 for the semiconductor, the thickness of the semiconductor layer is 1.2μm. Figure 1 shows the influence of the emission wavelength's variation and the thickness of the air/semiconductor layer on the reflectivity of the Bragg reflector constituted by four air-semiconductor pairs. Over a very wide wavelength band around 5.36μm, the reflectivity is almost the same. Even if ±10% differences from the designed thicknesses were produced in fabrication, there is still a high reflectivity near the wavelength of 5.36μm.

During the fabrication, a SiO_2 layer was deposited on the QCL structure, followed by a photoresist layer mask on the top of the SiO_2 layer. With the thickness of the air/semiconductor layer mentioned above, the patterns of the 22μm-wide ridge and the four-pair Bragg reflector were written on the photoresist layer by photo lithography. Then, the patterns were transferred to the SiO_2 layer by dry etching SiO_2 and the PMMA was cleared by boiling in acetone. Subsequently, inductively coupled plasma (ICP) etching with $Cl_2/O_2/Ar$ atmosphere was used to transfer the patterns to the QCL structure for the second time. Figure 2 shows the scanning electron microscope image of an etched sample. Due to the diffraction effect of photo lithography on the margin of the exposure region, the actual thicknesses were 1.4 and 1.1μm for the air and semiconductor layer, respectively. However, they were both in the difference range of 10%, which exerts no influence on the reflectivity of the Bragg reflector.

The inset in Fig. 2 shows the SEM image of the sidewalls of the four air/semiconductor pairs and the active region of the QCL is labeled. The etching reached the InP substrate and the depth exceeded 5μm. Although the sidewalls are coarser than the

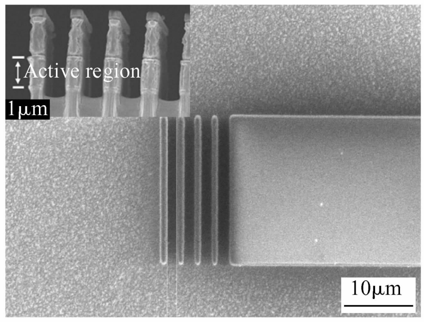

Fig. 2 Scanning electron microscopic image for a 22μm-wide four-pair Bragg reflector at one end of the QCL resonator The inset shows the SEM image of the perpendicular sidewalls of the four-pair Bragg reflector.

identical configuration reported in Ref. [7], the part of the active region is comparatively smooth and perpendicular. Considering the transmission of light is mainly in the active region, the effect of the Bragg reflector will not decrease much. Later, the SiO_2 layer on the structure with Bragg gratings patterns was cleared by the chemical etching and a new 450nm-thick SiO_2 layer was deposited on it. After an area for current injection was opened on the top of the ridge region, the Ti/Au contacts were evaporated. Then, the patterns of the QCL resonator, except the Bragg reflector, were covered with a photoresist layer, and the naked Ti/Au and SiO_2 layers were removed with aqua regia and HF solution, respectively. Finally, the photoresist layer was wiped off. The fabrication procedure promises an excellent insulator layer and electrical injection without any disturbance to the PhC region, which decreases the damages to the etched interface of the Bragg reflector.

The wafer was thinned down to 150μm and the bottom Ti/Au contacts were formed. Then it was cleaved into bars at the length of 2mm. Owing to the frangibility of the slim Bragg gratings, the devices were mounted epilayer-side up on copper heatsinks with indium solder and wire-bonded to ceramic contact pads. After fabrication, the lasers were mounted into a temperature-controlled liquid-nitrogen flow cryostat and current pulses of 1μs duration with a repetition rate of 5kHz were injected into the devices. The light emitting from the end without the PhC configuration of the laser cavity was collected and the operation was verified with a Bruker EQUINOX 55 Fourier transform infrared (FTIR) spectrometer in the step-scan mode. As shown in Fig. 3, the quasi-continuous-wave operation was confirmed through emission spectrum measurement and the wavelength was 5.36μm at 80K. Limited by the accuracy of our measurement devices, the optical output power can not be attained, which demonstrates a low optical power.

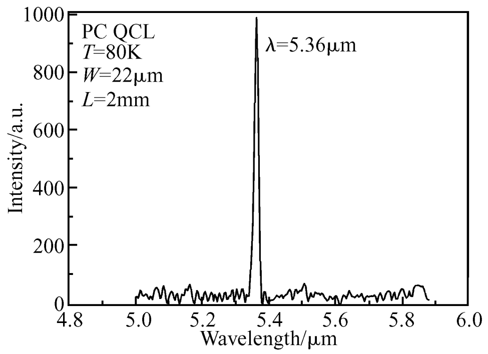

Fig.3 Emission spectrum of a 22μm-wide PhC QCL operated in pulsed mode

The inferior performances of the PhC QCLs result from the inevitable defects in the PhC fabrication process. The primary defect results from the strong diffraction effect of the photo lithography, which makes the margin of the patterns toothed. Another defect is the ragged etched interface produced by the dry etching, which influences the steepness of the Bragg gratings. Both defects increase the scatter of the laser in the Bragg reflector region, decrease the actual reflectivity, and, accordingly, weaken the effect of the 1D PhC. On the other hand, epilayer-up bonding was adopted to avoid damage to the slim gratings. It is very adverse to the heat dissipation from the active region, especially in the quasi-continuous-wave mode. More precise photo lithography and more accurate epilayer-down bonding technology are now in process.

3 Conclusion

In summary, we have presented the fabrication of a 1D PhC on a QCL structure with a simplified semiconductor fabrication technology. With the usual photo lithography and inductively coupled plasma etching, four-period air-semiconductor couples are defined as 1D PhC at one end of the resonator. The quasi-continuous-wave operation is demonstrated with the wavelength of 5.36μm for a 22μm-wide and 2mm-long, epilayer-up bonded PhC QCL. The shortcomings of the simplified fabrication are analyzed in detail.

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5.36μm InP 基一维光子晶体量子级联激光器*

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摘要：制作了基于 InP 基量子级联激光器的一维光子晶体.采用普通光学曝光的方法代替电子束曝光,结合反应耦合等离子刻蚀,在激光器的一侧腔面制作出 4 个周期的空气/半导体对作为 Bragg 反射器.对于一个 22μm 宽,2mm 长的正焊器件,80K 下的光谱测试证实了其准连续激射,激射波长为 5.36μm.

关键词：量子级联激光器；光子晶体；准连续波
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