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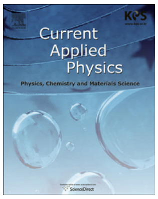

Fabrication and analysis of highly-reflective metal-dielectric mirrors for high-performance semiconductor laser applications

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ABSTRACT

The device performance improvement of ridge waveguide (RWG) laser diodes (LDs), operating at a wavelength (λ) of ~960 nm, with a metal-dielectric high-reflection (HR) mirror consisting of Au/Ti–SiO_2 layers on the back facet was demonstrated. To determine the optimum thickness of each layer, optical reflection calculations were performed using a rigorous coupled-wave analysis method, which leads to the resultant Au (80 nm)/Ti (5 nm)–SiO_2 (164 nm) layers. The layers exhibited a broad high reflection band of >91% over a wavelength range of 920–1000 nm, indicating the reflectivity of ~91.2% at λ ~ 960 nm. For 2 mm-cavity RWG LDs with the Au/Ti–SiO_2 HR mirror, an enhanced maximum output power (P_{max}) of 499.3 mW at an injection current of 3000 mA and a decreased threshold current (I_{th}) of 516 mA (i.e., P_{max} = 259.4 mW and I_{th} = 650 mA for the uncoated LDs) were obtained, showing an increased slope efficiency percentage of 82%. The external differential quantum efficiency was also increased from ~17.1 to ~31.1%. Also, the full widths at half maximum values of beam divergences of the device were 38° (vertical direction) and 4° (horizontal direction).

1. Introduction

Fabry–Perot cavity-based ridge waveguide (RWG) semiconductor laser diodes (LDs) with emission wavelengths close to 1 μm in the near-infrared (NIR) range have been widely used in a variety of applications including optical fiber communications, material processing, printing, medical instruments, and pumping sources for next-generation fiber lasers [1–4]. To realize high-performance lasing characteristics (i.e., reduced threshold current and increased output power) in LDs, efficient high-reflection (HR) mirror coatings at the rear facet can be one simple method. Generally, distributed Bragg reflectors (DBRs) consisting of many layers with optical quarter wavelength (λ/4) thicknesses of alternating high and low refractive index materials (e.g., SiO_2/TiO_2, SiO_2/Ta_2O_5, SiO_2/poly-Si, Al_2O_3/TiO_2, etc.) have been usually employed in LDs as a rear HR facet mirror [5–8]. However, their reflectivity and bandwidth depend strongly on the refractive index contrast of the constituent materials [9,10].

To obtain a high reflectivity over a wide wavelength range, furthermore, a high refractive index contrast is required, but this is also limited by the lack of availability of semiconductor materials with low refractive index. Additionally, conventional DBRs with several pairs (e.g., >5–6) composed of two different semiconductor materials have fundamental limitations such as low refractive index contrast, desirable material selection, thermal expansion mismatch, accurate layer thickness control, etc. [11,12]. On the other hand, metallic coating can be a simple and effective method to realize the HR mirror. The metallic coating technique has been widely applied in LDs, light-emitting diodes, and photodetectors [13–19]. However, the electric blocking layer is needed to prevent an electrical short in devices [20]. In this respect, SiO_2, which is one of the simplest materials with high melting point, high hardness, chemical stability, and easy deposition, has been widely used as an insulator in various electronic and optical devices. A more important fact is that the SiO_2 does not absorb ($k = 0$) the light over a NIR wavelength region, which can lead to a good optical performance.

In this work, we fabricated metal-dielectric HR mirrors consisting of Au/Ti–SiO_2 layers, which were simply deposited at the

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rear facet of RWG GaAs/InGaAs quantum well (QW) LDs operating at a wavelength of ~960 nm by using an electron (e)-beam evaporation system. To get a high reflectivity of Au/Ti–SiO_2 layers, their optimum thicknesses were determined by rigorous coupled-wave analysis (RCWA) simulations. Finally, the influence of Au/Ti–SiO_2 HR mirror coating at the rear facet on the device characteristics (i.e., light-current-voltage (L-I-V), far-field pattern, and emission spectrum) of LDs was explored.

2. Experimental and numerical simulation details

Fig. 1 shows the schematic diagram of the RWG GaAs/InGaAs QW LD chip structure with the metal-dielectric (Au/Ti–SiO_2) HR mirror at the rear facet. The GaAs/InGaAs QW epilayers of LDs operating at a wavelength (λ) of 960 nm were grown on GaAs substrates by using a metal-organic chemical vapor deposition system. The device structure is composed of n-AlGaAs clad, n-GaAs waveguide, GaAs/InGaAs QW, p-GaAs waveguide, and p-AlGaAs clad. The LDs with a cavity length of 2 mm were fabricated by conventional photolithography, lift-off, and etch processes. For current blocking and passivation, the SiO_2 layer was deposited by using a plasma-enhanced chemical vapor deposition system. Finally, the Au/Pt/Ti multilayer was deposited as ohmic contacts. For the fabrication of metal-dielectric mirror at the rear facet of LDs, 4N-purity Au granules and SiO_2 pellets were used as evaporation sources. For efficient adhesion between the Au and SiO_2 layers, a Ti layer with a thickness of 5 nm was deposited. All the Au, Ti, and SiO_2 layers were coated by using an e-beam evaporation system. The base pressure of chamber was evacuated to $<1 \times 10^{-6}$ Torr by using a cryogenic pump system. The deposition rate was kept at 0.1 nm/s with 10 rpm substrate rotation. To investigate the effect of Au layer thickness on the reflectivity of Au/Ti–SiO_2 mirrors, samples with different Au layer thicknesses of 20, 50, 80 and 110 nm were prepared on glass substrates with a 5 nm-thick Ti layer. The deposited profile of Au/Ti–SiO_2 mirrors was observed by using a scanning electron microscope (SEM; LEO SUPRA 55, Carl Zeiss). The surface roughness of the samples was evaluated by using an atomic force microscope (AFM; XE150, PSIA). To measure the optical properties, a UV–vis–NIR spectrophotometer (Cary 5000, Varian) with an integrating sphere was used at near normal incidence of ~3°. To characterize the device performance, the LD chips were attached on the high-quality copper (Cu) heat sink using an indium solder for a bottom contact and then wire-bonded by Au to contact pads for a top contact. Afterward, the chips bonded onto the Cu heat sink were loaded on the Cu mounts with a thermo-electric cooler and a thermistor. Here, we simply study a device feasibility of Au/Ti–SiO_2 HR mirror and thus the LDs were bonded with a junction-up structure, while most of LDs are usually soldered by junction-down scheme for good heat sinking. During the measurement of device characteristics, the temperature was maintained at room temperature (i.e., 298 K). Under continuous-wave (CW) mode, L-I-V characteristics were measured by using a probe station system incorporated with an integrating sphere and a calibrated photodetector.

For theoretical optical analyses, reflectance calculations of the Au/Ti–SiO_2 mirrors were performed using a RCWA method at normal incidence in a commercial software package (*DiffractMOD*, Rsoft Design Group). The thicknesses of Au and SiO_2 layers were varied in the ranges of 0–140 nm and 0–1000 nm, respectively. The thicknesses of Ti, glass, and GaAs layers were set to be 5 nm, 500 μm, and 500 μm, respectively. The refractive index and extinction coefficient of the constituent materials used in these calculations were acquired from the index Web site [21].

3. Results and discussion

Fig. 2 shows (a) the measured reflectance spectra of the Au/Ti layers on glasses for different thicknesses of Au layer and (b) the contour plot of variations of the calculated reflectance spectra of the Au/Ti layers as functions of wavelength and Au layer thickness. The light entered from air to the glass/Ti/Au structure and the thickness of Ti layer was 5 nm. As shown in Fig. 2(a), for the Au/Ti layers on glasses, the reflectivity was strongly influenced by the Au layer thickness. As the Au layer thickness was increased from 20 to 110 nm, the reflectance was increased from 72.9 to 92.5% at $\lambda = 960$ nm. However, for 50 nm-thick Au layer, the reflectance values of >90% were obtained over a wide wavelength range of 920–1000 nm. Furthermore, for 80 nm-thick Au layer, the reflectivity of the Au/Ti layer was nearly saturated at ~92.1% at $\lambda = 960$ nm. In RCWA simulations of Fig. 2(b), for different Au layer thicknesses, similar reflectance properties of the Au/Ti layers on glass are observed. At the Au layer thicknesses around 50 nm, the Au/Ti layers show high reflectance values of ~90% in the wavelength range of 920–1100 nm. The inset of Fig. 2(b) shows the calculated reflectance value of the Au/Ti layers on glass at $\lambda = 960$ nm. This indicates that the reflectivity is abruptly increased by ~92% up to the Au layer thickness of 60 nm and almost saturated at ~93% for the Au layer thicknesses above 80 nm. Thus, as the HR facet mirror

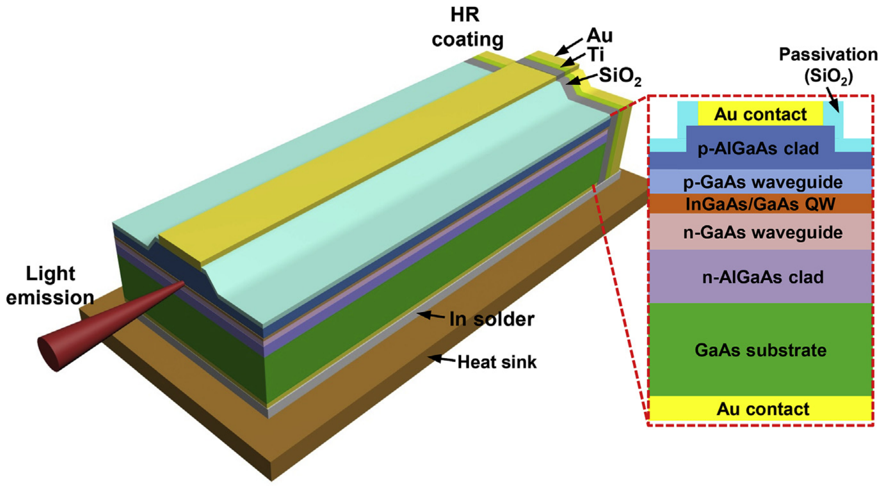

Fig. 1. Schematic diagram of the RWG GaAs/InGaAs QW LD chip structure with the metal-dielectric (Au/Ti–SiO_2) HR mirror at the rear facet.