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ZnTe/GaSb distributed Bragg reflectors grown on GaSb for mid-wave infrared optoelectronic applications

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ZnTe/GaSb distributed Bragg reflectors (DBRs) are proposed and demonstrated for mid-wave infrared (2–5 μm) optoelectronic applications. The reflectance spectra of ZnTe/GaSb DBRs are simulated using the transmission matrix method, indicating a peak reflectance higher than 99.9% for a DBR of 10 quarter-wavelength ($\lambda/4$) pairs. A series of ZnTe/GaSb DBR structures have been successfully grown on GaSb (001) substrates using molecular beam epitaxy. X-ray diffraction results reveal smooth interfaces, uniform thicknesses, and low defect density. The DBR sample of seven $\lambda/4$ pairs has a peak reflectance as high as 99.0% centered at 2.5 μm with a 480-nm wide stopband. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4753819]

The mid-wave infrared (MWIR) wavelength range between 2 and 5 μm contains absorption lines of several atmospheric pollutants, such as CO, CH_4, NO_2, NH_3, and HF. Therefore, semiconductor lasers in this spectral range are highly attractive light sources for gas detection and spectroscopy applications. Since vertical-cavity surface-emitting lasers (VCSELs) offer low power consumption and ease of monolithic integration with microelectromechanical system (MEMS) structure for wavelength tuning,[1–4] much research effort has been devoted to InP-based and GaSb-based near-infrared (NIR) and MWIR VCSELs.[5–8] While InP-based VCSELs have reached emission wavelengths up to 2.3 μm,[9] GaSb-based VCSELs have covered a spectral range beyond 2.6 μm.[10] As is well known, the optical cavity in a VCSEL needs the use of high reflectivity mirrors, usually in the form of distributed Bragg reflectors (DBRs). Unfortunately, almost all the III-V semiconductors lattice-matched to InP and GaSb offer very small refractive index differences, which are crucial for the realization of thin DBRs with high reflectivity to reduce the threshold current density. It is therefore highly desirable to develop DBR structures that are both lattice-matched to GaSb and have a high refractive index contrast along with broad wavelength tunability for monolithically integrated tunable VCSELs technology.

Recently, a new materials platform consisting of 6.1-Å semiconductors grown on GaSb and InAs substrates was proposed for optoelectronic devices.[11,12] This materials platform consists of both II–VI (MgZnCdHg)(SeTe) and III–V (InGaAl)(AsSb) compound semiconductors, which have direct bandgaps spanning the entire energy spectrum from far-infrared (~0 eV) up to ultraviolet (~3.4 eV). The broad range of bandgaps and material properties make it very attractive for a wide range of applications in optoelectronics, such as photodetectors, solar cells, laser diodes, and light emitting diodes. Among materials in this platform, ZnTe and GaSb are known to be closely lattice-matched with a lattice mismatch of only 0.13%. High quality ZnTe/GaSb and GaSb/ZnTe heterostructures have already been successfully demonstrated with very low density of misfit dislocations.[13,14] Furthermore, GaSb and ZnTe have a large refractive index contrast in the MWIR range (for example, $\Delta n = 1.18$ at 0.6 eV[15]). This refractive index contrast is significantly higher than those of InGaAs/InAlAs ($\Delta n = 0.27$) and AlAsSb/GaSb ($\Delta n = 0.6$), which have been widely used for DBRs in VCSELs emitting in the MWIR spectral range.[9,16] As a result, DBR structures consisting of ZnTe and GaSb can provide very high reflectivity with significantly fewer pairs of quarter-wavelength ($\lambda/4$) layers. Consequently, the overall thicknesses of DBR structures can be greatly reduced. In this work, we propose and demonstrate the ZnTe/GaSb DBRs that can be potentially used in VCSELs for MWIR optoelectronic applications.

To properly design the DBR structures, a quantitative study of the reflectivity of the proposed ZnTe/GaSb $\lambda/4$ structures was carried out using the transmission matrix method.[17] The transmission matrix formulation is expressed as follows:

$$\begin{bmatrix} B \\ C \end{bmatrix} = \left(\prod_{q}^{2N} \begin{bmatrix} \cos\Delta_q & i \cdot \sin(\Delta_q)/n_q \\ i \cdot \sin(\Delta_q) \cdot n_q & \cos\Delta_q \end{bmatrix} \right) \cdot \begin{bmatrix} 1 \\ n_{sub} \end{bmatrix}, \tag{1}$$

$$\Delta_q = 2\pi n_q \cdot d_q/\lambda, \tag{2}$$

$$d_q = \frac{\lambda_{peak}}{4 \cdot n_q}, \tag{3}$$

where N is the number of $\lambda/4$ pairs, n_q and n_{sub} are the refractive indices of the q^{th} layer and the substrate, respectively, d_q is the thickness of the corresponding $\lambda/4$ layer, and λ_{peak} is the peak wavelength of the high reflectance band, which is set as 2.3 μm for the simulation. The reflectance is given by

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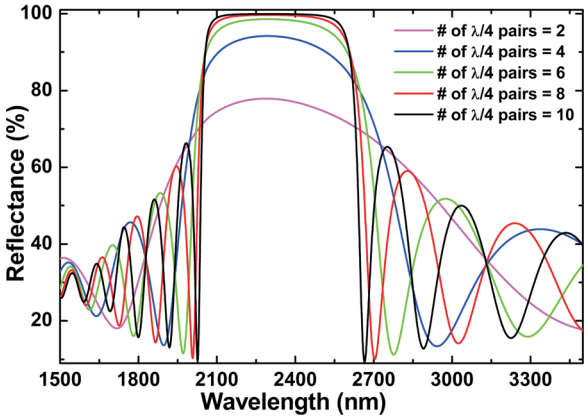

FIG. 1. Simulated reflectance spectra for ZnTe/GaSb DBRs with different numbers of $\lambda/4$ pairs.

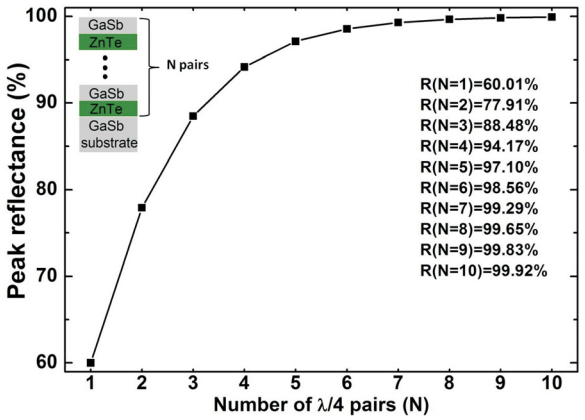

FIG. 2. Peak reflectance versus number of $\lambda/4$ pairs.

$$R = \left(\frac{1 - C/B}{1 + C/B}\right) \cdot \overline{\left(\frac{1 - C/B}{1 + C/B}\right)}, \tag{4}$$

where C/B is also referred to as optical admittance.

In the simulation, measured refractive indices of bulk ZnTe and GaSb are used.[18] Dispersion curves of ZnTe and GaSb refractive indices in the spectral range from 0.2 to 0.7 eV are parameterized and extracted using the Sellmeier equation.[19] With refractive indices, layer thicknesses, and the numbers of $\lambda/4$ pairs as input parameters, reflectance spectra of the ZnTe/GaSb DBR structures are simulated using Eq. (4), as shown in Figure 1. The relationship between the peak reflectance and the number of $\lambda/4$ pairs is also plotted in Figure 2. It is clearly seen that the reflectance higher than 99% can be expected from the ZnTe/GaSb DBR consisting of only seven $\lambda/4$ pairs. For the ZnTe/GaSb DBR of 10 pairs, a reflectance as high as 99.9% can be achieved. It is worth noting that the reflection spetra show a very wide and flat stopband, as expected due to the large refractive index contrast between ZnTe and GaSb. By using ten $\lambda/4$ pairs, the bandwidth of primary reflectance band above 99% is 428 nm. Comparisons of main DBR design parameters and peak reflectance are made among ZnTe/GaSb, AlAsSb/GaSb, and InGaAs/InAlAs DBRs. As shown in Table I, only ten $\lambda/4$ pairs are needed to reach 99.9% reflectance for ZnTe/GaSb DBRs, while the other two DBRs require as many as 20 and 30 pairs, respectively. As a result, the thickness of overall ZnTe/GaSb DBR structure can be reduced to 4 μm or less, vs. 7 to 11 μm for the other two structures.

A set of ZnTe/GaSb DBR samples were grown using a molecular beam epitaxy (MBE) system consisting of two separate II–VI and III–V growth chambers connected by an ultrahigh-vacuum (UHV) transfer module. The DBR structures were grown on a GaSb (001) substrate with an unintentionally doped GaSb buffer layer. During the growth, ZnTe epilayers were deposited at 320 °C in the II–VI chamber, while GaSb epilayers were grown in the III–V chamber using a temperature ramp method to protect the ZnTe layer surfaces and to achieve high material quality.[14] The wafer was transferred between II–VI and III–V chamber repeatedly to complete the whole DBR structure. The detailed growth conditions, such as growth temperatures, temperature ramping rate, BEP ratios, and growth rates were reported previously.[14]

After completion of the growth, x-ray diffraction (XRD) patterns of the samples were measured in the vicinity of the (004) diffraction peak of the GaSb substrate using a PANalytical X'Pert PRO MRD x-ray diffractometer with multicrystal monochromator. The copper $K_{\alpha 1}$ line (1.54 Å) was used as the incident beam. The (004) ω-2θ curve for the DBR sample of four $\lambda/4$ pairs is shown in Figure 3. Pendellösung fringes are clearly observed, indicating high interface smoothness, as well as excellent composition and thickness uniformities of all the layers. The (004) XRD pattern is also simulated using X'Pert Epitaxy software. The ZnTe and GaSb layer thicknesses are set equal to 190 and 135 nm, respectively, as estimated from the growth rates. The simulated results show excellent agreement with the experimental curve.

The reflectance measurements were carried out at normal incidence using a Globar as the light source. The incident light passed through an optical microscope and was focused on the samples surface. The reflectivity spectra were measured by a Fourier transform infrared (FTIR) spectrometer equipped with a CaF_2 beam-splitter and a liquid-nitrogen-cooled HgCdTe detector. As seen in Figure 4, the measurement result for the DBR sample of seven $\lambda/4$ pairs shows a peak reflectance of 99.0% with a wide stopband of 480 nm centered at 2.5 μm.

TABLE I. Comparison of different DBRs used for VCSELs emitting at 2.3 μm.

[DBR materials]/substrate	Refractive index contrast (Δn)	Number of $\lambda/4$ pairs (N)	Calculated peak reflectivity (%)	Total thickness (μm)
[ZnTe/GaSb]/GaSb	1.18	10	99.9	3.6
[AlAsSb/GaSb]/GaSb	0.6	20	99.7	6.6
[InGaAs/InAlAs]/InP	0.27	30	99.4	10.5

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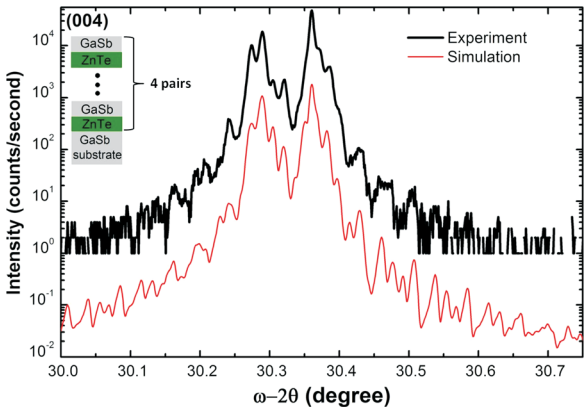

FIG. 3. Measured and simulated XRD patterns for a ZnTe/GaSb DBR sample of four $\lambda/4$ pairs.

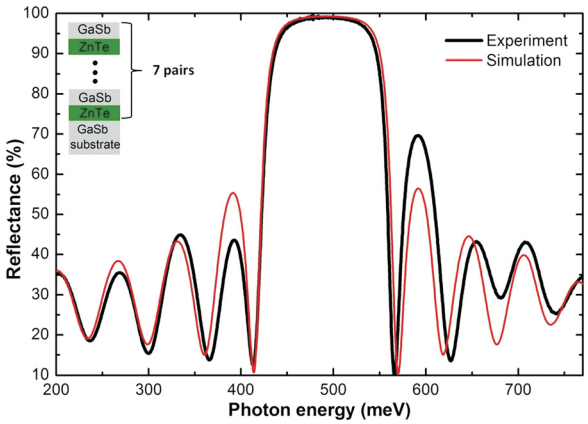

FIG. 4. Measured and simulated reflectance spectra for a ZnTe/GaSb DBR sample of seven $\lambda/4$ pairs.

Simulation of reflectance spetra was also performed. By comparing the simulation results with the experimental data, excellent agreement is obtained in terms of peak reflectance, bandwidth of photonic stopband, and sidelobe positions.

In summary, ZnTe/GaSb DBR structure is proposed for applications in mid-wave infrared VCSELs and other optoelectronic devices. Numerical simulation using the transmission matrix method shows that a peak reflectance as high as 99.9% can be expected from ZnTe/GaSb DBRs with only 10 pairs $\lambda/4$ layers. Successful growth of high quality ZnTe/GaSb DBRs has been demonstrated on GaSb (001) substrates using MBE. High-resolution XRD results show narrow line widths and distinctive Pendellösung fringes from ZnTe and GaSb epilayers, indicating smooth morphology, uniform thickness, and low defect density. A peak reflectance of 99.0% with a wide stopband of 480 nm centered at 2.5 μm was experimentally demonstrated for a ZnTe/GaSb DBR with only seven $\lambda/4$ pairs.

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