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Dielectric coatings for infrared detectors

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The application of plasma enhanced chemical vapor deposition technique to fabricate SiO_2/Si_3N_4 coatings for resonant cavity enhanced photodetector operating in the near-infrared range at 1550 nm is considered. The conditions required to deposit high quality distributed Bragg reflector (DBR) are discussed. Optical properties of dielectric films fabricated are presented. Experimentally observed reflectivity of the mirrors is compared with the one numerically predicted for DBRs.

Keywords: plasma enhanced chemical vapor deposition (PECVD), dielectric mirror, infrared photodetectors.

1. Introduction

For proper operation of the semiconductor photodetectors the dielectric coatings are necessary. Those coatings depending on the particular design of the device have to assure certain optical parameters, most often ultralow or ultrahigh reflectivity. The low reflectivity coatings allow avoiding the light reflection at the air-semiconductor interface due to the high discontinuity of the refraction index ($n \cong 1$ for air and $n = 3.5$ for GaAs). Nowadays the antireflection layers with the reflective index lower than 10^{-6} are routinely deposited. They allow efficient penetration of the light into the photodetector active region, *i.e.*, enhancement of the device quantum efficiency.

There is also a great need for high reflectivity layers. They are required, for instance, in same design of resonant-cavity enhanced photodetectors (RCE-PD) for enclosing the cavity [1]. The highly reflective coatings can be formed by a simple metal layer. This is the simplest realization, however, it has two handicaps: the reflectivity of the metal mirror is limited to 0.98 (air/silver) and in certain designs of photodetectors, which are fabricated by planar semiconductor technology they cannot be used on the substrate side. This is so in the case of the resonant cavities. In order to overcome these disadvantages the distributed Bragg reflectors (DBR) are fabricated.

The DBR are made as a stack of alternate semiconductor or dielectric layers of high- and low-refractive index, with each layer in the stack having an optical thickness of quarter-wavelength. The light focused on such a stack undergoes multiple reflections at each interface, which results in the creation of a number of light waves with different phases, and consequently, due to positive interference the reflected light is enhanced and the traveling through is diminished. As a result, the mirrors of extremely high reflectivity much exceeding those of a silver mirror can be fabricated and the more reflectivity of the DBR can be freely designed by changing the number of the layers or the refraction index contrast.

Although the DBRs are well known and described in many papers, they still are of current interest. The reason is the fabrication technology, which is slightly difficult and tricky.

The reflectivity spectrum of the mirror is determined by the layer refractive index, *i.e.*, composition and layer thickness. The high accuracy of those parameters for each pair of layers, together with low absorption and low scattering losses, has to be ensured during the growth of all layers to obtain high reflectivity mirrors. In order to avoid the unwanted modification of the device operation upon the deposition of thick stack of the dielectric layers, in some cases a few micrometers, the film stresses have to be considered. The stress is reducted within a single layer by proper choice of deposition parameters or stress compensation within multilayer systems [2, 3].

In this paper, we show the application of plasma enhanced chemical vapor deposition (PECVD) technique towards the deposition SiO_2/Si_3N_4 coatings for use in the near-infrared range RCE-PD. In these devices both high bandwidth and high quantum efficiency can be achieved simultaneously due to multipass of infrared radiation that results in an efficient absorption in thin absorbing layer. High values of both parameters have been obtained for InGaAs/InP RCE-PDs fabricated. The devices are dedicated for high speed detection of 1550 nm infrared radiation [4]. Front mirrors as well as active layers of InGaAs/InP RCE-PDs are grown by molecular beam epitaxy (MBE). Top mirrors of the devices are of hybrid type and consist of dielectric Bragg reflectors and metallic layer.

We describe PECVD technique, the method required to calibrate the deposition of layers of which the DBR stock consists. Further we show the optical quality of the mirrors by reflectivity measurements compared with numerically designed DBRs.

2. Experimental details

We have fabricated a number of DBRs consisting of SiO_2 and Si_3N_4 layers using direct PECVD technique (conventional plate reactor R&D series, Plasmalab System 100 Oxford). Two generators (13.56 MHz and 100–450 kHz) with impedance matching systems were applied for plasma excitation. All processes were carried out at a temperature of 300°C. *In-situ*, the layer thickness was controlled considering their respective deposition times, by assuming constant deposition rates. *Ex-situ*, a single layer thickness was measured using a He-Ne laser ellipsometer (Gaertner, 632.8 nm).

The optical quality of the SiO_2 and Si_3N_4 films deposited on silicon wafers was evaluated for refraction index and extinction coefficient by variable angle spectroscopic ellipsometer (VASE) of J.A. Woollam Inc. Co. Ellipsometric measurements were carried out for each wafer in a wide spectral range (600–1600 nm) at two angles of

T a b l e. Plasma deposition conditions of SiO_2 and Si_3N_4 films for low stressed DBRs.

Condition	Silicon oxide	Silicon nitride	
Frequency (pulse time)	13.56 MHz	13.56 MHz (32 sec)	100 kHz (8 sec)
Power	16 W	15 W	21 W
Generator mode	Continuously	Alternately	
Pressure	1 torr	1 torr	
Temperature	300°C	300°C	
Flow rate of silane 2% in N_2	1125 sccm/min	1000 sccm/min	
Flow rate of nitrous oxide	750 sccm/min		
Flow rate of ammonia		20 sccm/min	

incidence (65°, 75°). The optical model, which was used for spectro-ellipsometric data analyses, consisted of silicon dioxide layer or silicon nitride and silicon substrate. The Cauchy dispersive model [5] allowed determination of the silicon dioxide and silicon nitride refractive index and their thicknesses.

The first step in fabrication of the stress free multilayer stacks was the calibration of proper deposition condition separately for each of the layer types. The calibration layers were deposited on Si, GaAs and quartz substrates. For each individual film the stress was determined from the measurement of the bending of the substrates (3 inch ⟨111⟩ silicon wafers). The curvature was measured by optical method using FLX2320 Tencor. The modified Stoney's dependence decribed in many papers (*e.g.* [6]) was used for stress calculations.

The conditions of deposition of silicon oxide were set for standard process to get low (100 MPa) compressive stress, as summarized in the Table.

In the case of silicon nitride films a variety of techniques exists to control stress. During the deposition, the stress can be varied by gas flow, power and frequency modulation. The most versatile of these is frequently modulation. This involves the use of two generators operating typically under high- and low frequency conditions. High frequency PECVD (13.56 MHz) produces tensile nitrides, whereas low frequency PECVD (100 kHz) produces compressive films. Thus, by varying the modulation percentage of one frequency onto the other we are able to alter the nitride film stress from tensile (max 500 MPa) through to compressive one (max 1000 MPa). This in the case of DBR allows us to compensate the compressive stress of silicon oxide layers by tensile stress of silicon nitride and, in consequence, to fabricate a stress-free thick layer stack. The applied deposition process conditions are summarized in the Table, too.

The results of the measurement of the refraction index and extinction coefficient in the layers formed under conditions presented are shown in Fig. 1.

Finally, the reflectivity of the test structures was measured. The measurements were performed using two-beam absorption spectrophotometer (LAMBDA type) in the spectral range: from 1000 to 2000 nm. The optical set-up of this spectrometer, equipped with reflectance option, is similar to the standard one used for reflectance

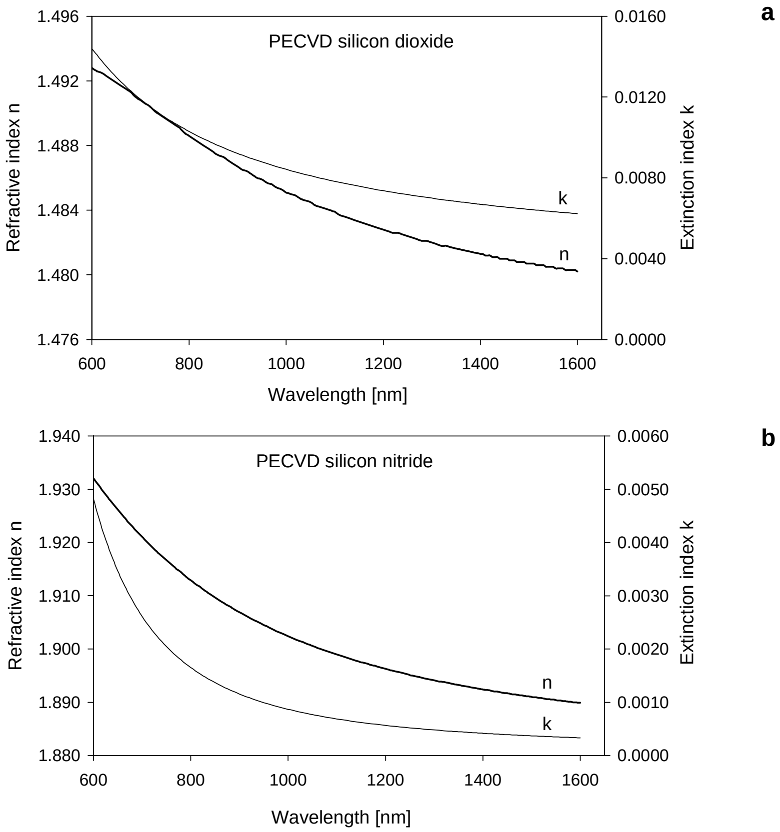

Fig. 1. Spectral dependence of refractive indexes and extinction coefficients for our PECVD SiO_2 (**a**) and PECVD Si_3N_4 (**b**).

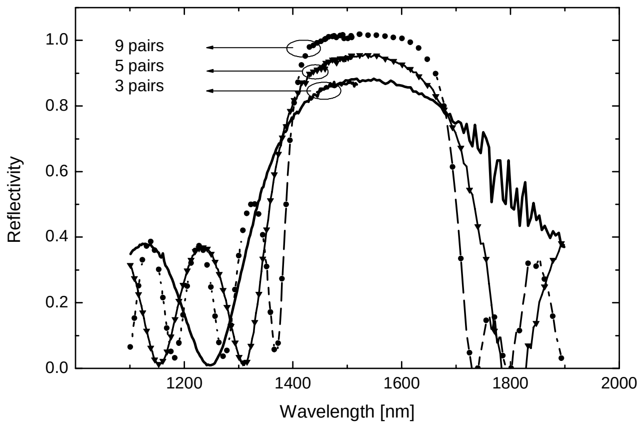

Fig. 2. Reflectivity spectra of DBRs consisting of 3, 5 and 9 pairs of SiO_2/Si_3N_4 deposited on silicon substrates.

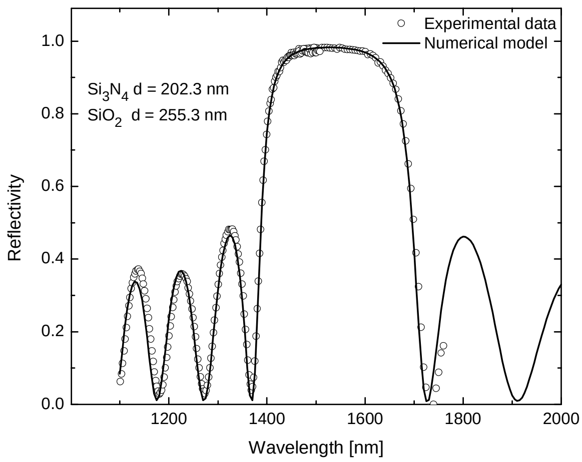

Fig. 3. Reflectivity spectra of DBR consisting of 9 pairs of SiO_2/Si_3N_4 deposited on silicon substrate.

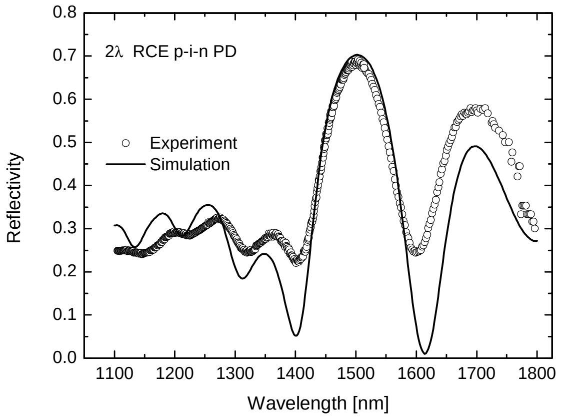

Fig. 4. Measured and simulated spectral reflectivity of the RCE *p-i-n* PD. Backside illumination.

measurement [7]. The data for the structures consisting of three, five and nine SiO_2/Si_3N_4 pairs is collected in Fig. 2.

An increase in reflectivity with the number of low and high index layers follows the predictions of the numerical calculation based on the transfer matrix methods. There is an excellent agreement between the experimental data and the numerical model (Fig. 3).

The reflectivity spectra taken in the same way for the resonant-cavity enhanced heterostructures are presented in Fig. 4. The heterostructure consisted of: 7 pairs of $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$:Si layers forming bottom DBR, and 9 pairs of SiO_2/Si_3N_4 layers forming top dielectric DBR. Absorber and two spacer layers were made of undoped $In_{0.53}Ga_{0.47}As$ (140 nm thick) and $In_{0.52}Al_{0.48}As$ (283 nm and 493 nm) layers, respectively. The structure was grown on n^+ InP substrate.

The reflectivity spectra obtained reproduce features expected from numerical simulations for good quality structures. High reflection in the range of 1500–1550 nm has been detected. The measurements have been performed on epitaxially grown structures without any metallic reflector deposited on the top. Small changes in the maximum reflection position have been found. They result from fluctuations of layer thickness across the wafer. The RCE devices are found to be very sensitive for such fluctuations because 1% change of layer thickness corresponds to 15 nm displacement of the resonance line.

3. Summary

The PECVD process deposition of silicon oxide and silicon nitride described allows fabrication of high quality dielectric DBRs as top mirror of photodetectors designed for 1550 nm operation. Useing these DBRs high quantum efficiency of the devices can be obtained. The PECVD technique is suitable for laser-photodetector integrated system fabrication process.

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