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Characterization of a-Si:H/SiN multilayer waveguide polarization using an optical pumping application—LED*

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Abstract: This paper describes the fabrication of a waveguide and the analysis of its polarization characteristics by applying light-emitting diode (LED) pumping lights to its surface. By using double tubed coaxial line (DTCL) microwave plasma chemical vapor deposition (MPCVD) equipment, an a-Si:H/SiN multilayer waveguide was fabricated whose thickness could be controlled at nanometer order. The main structural material of the waveguide sample consisted of a combination of layers of amorphous silicon hydrogen and silicon nitrate. Once the sample was ready, another major objective of the experiment was to analyze the polarization characteristics of the fabricated waveguide. The idea of the experiment was to analyze how the waveguide reacts when three types of LED (blue, yellow, and red) are radiated onto its surface. The results showed that the fabrication of the a-Si:H/SiN sample is successful. Most effective transmission results, which accord with the polarization characteristics analysis, were obtained.

Key words: Waveguide, Multilayer, Optical pumping, Light-emitting diode (LED), Double tubed coaxial line microwave plasma chemical vapor deposition (DTCL-MPCVD)
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INTRODUCTION

Optical pumping is a process in which light is used to excite (or ‘pump’) electrons from a lower energy level in an atom or molecule to a higher one (Goure and Verrier, 2002; Maeda, 2004); i.e., the electrons from the external light energy source will cause the optical signal transmission to be amplified (Kato, 1987). It is recognized that optical pumping is a very important process in optical communication, especially in optical amplification. It is important in ensuring that the optical signal transmitted through a communication medium is always at the desired energy level.

Previous research focused mainly on optimizing the parameters of a-Si:H/SiN waveguide structure with the aim of fabricating the waveguide sample with the best parameters to be in nanometer order (Kato *et al.*, 2001; Ojima *et al.*, 2003). One method introduced for fabricating the waveguide was microwave plasma chemical vapor deposition (MPCVD). By using the MPCVD method with parameters from previous research, an optical waveguide sample, a-Si:H/SiN, was fabricated in this research. This method was chosen for this study as it promises a low cost technology with high quality for producing large diamonds (Kezuka *et al.*, 2002; Yan *et al.*, 2002). The aim of this study was to examine how the extinction ratio of an optical signal applied through the fabricated a-Si:H/SiN optical waveguide sample is affected when three different wavelengths

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of light-emitting diode (LED) sources are pumped onto the sample surface.

METHODOLOGY

Fabrication process

Fig.1 shows the double tubed coaxial line type MPCVD (DTCL-MPCVD) equipment.

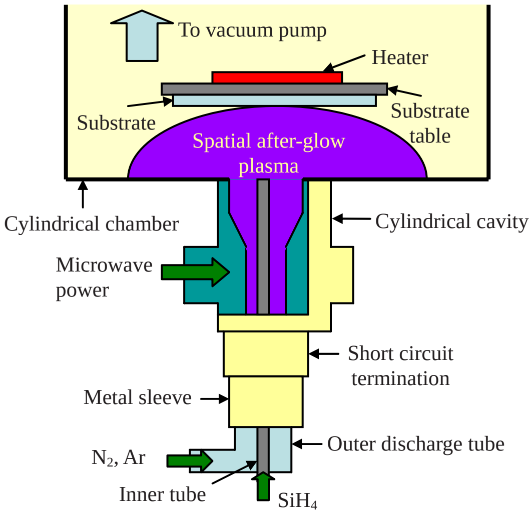

Fig.1 DTCL-MPCVD equipment

This equipment is divided into two areas: the discharge plasma area (lower part) and the spatial after-glow plasma area (upper part, cylindrical chamber) (Kato, 1987; Ojima *et al.*, 2003). The discharge plasma area is where the microwave electric power is supplied. The Ar and N_2 discharge gas flows through the outer discharge tube, and SiH_4 gas flows through the inner tube. By controlling the movement of a short circuit terminator and a metal sleeve using a computer-controlled program, an appropriate plasma condition can be created (JSPS, 1983; Kato, 1987; Saito *et al.*, 2003).

There are two short circuit terminators in this equipment. These will cause the reflection of the supplied microwave, and through *x*- and *z*-axis adjustment, an adequate standing wave can be created. An a-Si:H thin film fabrication process can be used to demonstrate the process. As microwave power is applied to the cylindrical cavity and Ar gas (discharge gas) flows through the outer discharge tube, plasma for Ar gas can be created. Next, SiH_4 gas (material gas) will flow through the inner tube to the cylindrical chamber. At the end of the discharge tube (the area between the discharge tube and the cylindrical chamber), SiH_4 gas from the inner tube and Ar gas from the outer discharge tube will undergo a chemical reaction (SiH_4 will dissociate) and form a condition known as the radical area (Kato, 1987; Kato *et al.*, 2001). The mixture will be transferred onto the silicon substrate to form an a-Si:H layer. The mechanism of this process is shown in Fig.2 (Kato, 1987; Kikuchi, 1987; Ojima *et al.*, 2003).

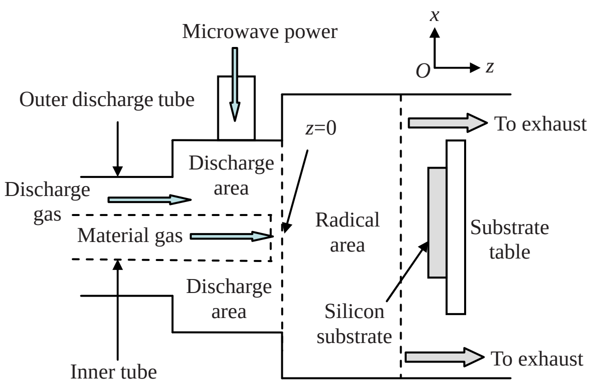

Fig.2 DTCL-MPCVD equipment mechanism (Ojima *et al.*, 2003)

Transmission characteristics

The equipment set used to analyze the optical transmission characteristics is shown in Fig.3. The wavelength of the laser source used for the experiment was 1.55 μm, which has the lowest loss spectrum in single mode silica fiber (Kokubun, 1999; Agrawal, 2002).

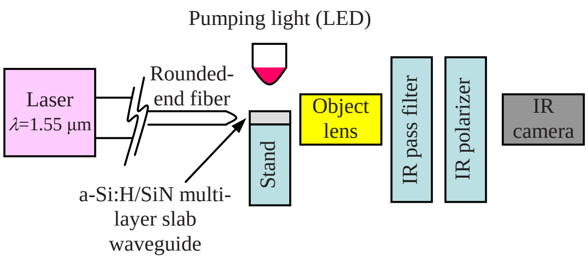

Fig.3 Equipment setup for optical transmission characteristics analysis

The laser source was then connected to a rounded-end fiber optic cable, which acts as a transfer medium for the laser. The cable was directed at the waveguide sample, which was put on a stand.

Pumping light (LED) used in the experiment was set perpendicular to the sample, which is vital to ensure that the LED radiated onto the sample surface is at the highest value. An infrared (IR) pass filter was used to filter all unnecessary light sources that might have influenced the results of the experiment. An IR polarizer acts as a filter that allows either TE mode or TM mode optical signal to pass through it. As the effect of TE and TM optical signals on the a-Si:H/SiN multilayer waveguide is the subject of other research, this study will focus only on the effect of the LED wavelength on the device. The image of the signal transmitted through the waveguide sample was captured using an IR camera connected to a computer. The light energy of the optical signal transmitted through the waveguide was then measured using equipment that can measure the illumination value of the signal (Kato *et al.*, 2001; Kezuka *et al.*, 2002; Melchiorri *et al.*, 2005).

THEORETICAL FRAMEWORK

A theoretical cross-section structure of the device fabricated from the MPCVD equipment is shown in Fig.4. The bottom part is the silicon substrate structure, on top of which is the a-Si:H/SiN waveguide. The basic structure of an optical waveguide is two clad layers with another layer, called the core layer, sandwiched between them (Kikuchi, 1987; Kokubun, 1999; Simmons and Potter, 2000).

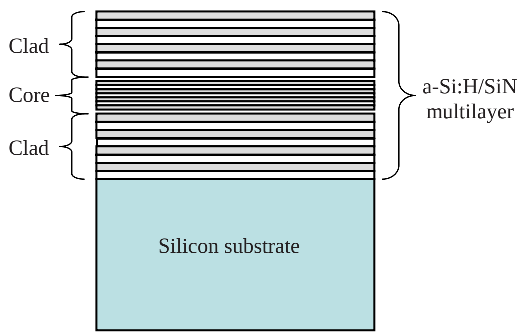

Fig.4 Cross-section structure of a-Si:H/SiN multilayer optical waveguide

Core thickness fixing calculation

In this case, since the core layer structures are made of a-Si:H and SiN, the refractive index value of the multilayer core is

$$n_1 = c / d,$$

where c and d are the thicknesses of the a-Si:H layer and the SiN layer, respectively. The refractive index value of the core layer (multilayer) is given by

$$n_2 = 2.65\frac{c}{c+d} + 1.78\frac{d}{c+d}, \tag{1}$$

where the index values of the a-Si:H layer and the SiN layer are 2.65 and 1.78, respectively. Based on the index values of the core and the clad, the relationship between t/λ (λ is the light wavelength and t is the core layer thickness) and the efficiency index value (n_{eff}), the most appropriate core thickness can be calculated by adjusting the thickness values of a-Si:H and SiN layers (Kato, 1989; Yoshida *et al.*, 2004). At this thickness, the optical signal is transmitted at its optimal performance, i.e., the core thickness that may have the lowest signal loss during transmission, referred to single mode optic (Kato, 1987; Kikuchi, 1987). A common equation based on TE mode or TM mode can be shown as

$$\frac{t}{\lambda} = \frac{1}{\pi\sqrt{n_1^2 - n_{\mathrm{eff}}^2}} \arctan\left|\left(\frac{n_{\mathrm{eff}}^2 - n_2^2}{n_1^2 - n_{\mathrm{eff}}^2}\right)^{1/2} + m\frac{\pi}{2}\right|, \tag{2}$$

$$\frac{t}{\lambda} = \frac{1}{\pi\sqrt{n_1^2 - n_{\mathrm{eff}}^2}} \arctan\left|\frac{n_1^2}{n_2^2}\left(\frac{n_{\mathrm{eff}}^2 - n_2^2}{n_1^2 - n_{\mathrm{eff}}^2}\right)^{1/2} + m\frac{\pi}{2}\right|, \tag{3}$$

respectively, where m is an integer. The relationship between t/λ and n_{eff} can be shown as in Fig.5 (Kato *et al.*, 2001; Pierantoni *et al.*, 2005).

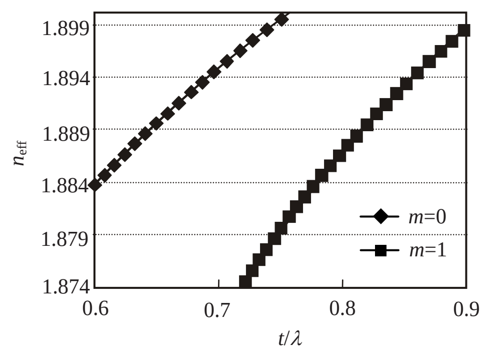

Fig.5 Relationship between t/λ and the efficiency refractive index n_{eff} (Kato *et al.*, 2001)

Based on Fig.5, if we fix the t/λ value, the value of n_{eff} will determine the mode numbers. In the single mode case (fundamental mode, m=0), it can be concluded that when the value of n_{eff} is maximum, the core thickness t is at its most appropriate value (Kato *et al.*, 2001; Ojima *et al.*, 2003).

EXPERIMENTAL RESULTS

Waveguide fabrication

The conditions of the fabrication process for the clad and core are shown in Tables 1 and 2, respectively. Note that the thickness value for each layer shown in the tables is estimated based on calculation theory. The next process is to proceed to the a-Si:H/SiN fabrication process using the MPCVD equipment. Fig.6 shows an image of a cross section of the fabricated waveguide taken using a transmission electron microscope (TEM). The a-Si:H layers and SiN layers can be clearly distinguished. The figure also shows the core multilayer sandwiched between two clad multilayers (Kato *et al.*, 2001; Niira *et al.*, 2003; Ojima *et al.*, 2003).

Table 1 Parameters in the clad fabrication process

Parameter	Value	
	a-Si:H layer	SiN layer
Discharge gas flow (ml/min)	110*	140**
SiH_4 gas flow (ml/min)	5	5
Applied microwave power (W)	150	270
Reflected microwave power (W)	0	0
Gas exhausting time (s)	100	100
Discharge waiting time to change gas (s)	40	40
Substrate voltage potential (V)	0	0
Substrate temperature (°C)	250	250
Inner tube's tip position (cm)	z=−1.4	z=−1.4
Substrate position (cm)	z=10	z=10
Substrate area (cm^2)	40	40
Discharge time (s)	180	20
Estimated thickness (nm)	30	90
Number of phases	18	18

* Ar gas; ** N_2 gas

Table 2 Parameters in the core fabrication process

Parameter	Value	
	a-Si:H layer	SiN layer
Discharge time (s)	90	10
Estimated thickness (nm)	10	45
Number of phases	11	11

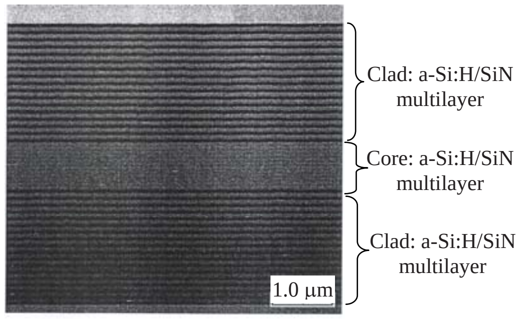

Fig.6 a-Si:H/SiN multilayer slab waveguide cross cut image (TEM image)

Transmission characteristics analysis

1. Hypothesis

Before starting the experiment on the transmission characteristics of the device, it is important to understand the idea of the main law of the pumping lights that are used in this activity. Basically, the main purpose of these pumping lights (red, blue, and yellow LEDs) is to excite the electrons in the waveguide (a-Si:H layers) so that when the excitation happens, it may increase the reflection of TE mode optical signal transmission when the light passes through the waveguide. The hypothesis for this experiment is as follows:

Hypothesis From past research results, the optical band gap energy for a-Si:H is E_g=2.2 eV (Kato *et al.*, 2001). Hence,

$$\lambda = hc / E_g = 563\,\text{nm}, \tag{4}$$

where E_g is the band gap energy for a-Si:H to emit light, h is Plank's constant, λ is the wavelength, and c is speed of light in vacuum. We suggest that pumping light with a wavelength lower than 563 nm would be more effective in this experiment (Simmons and Potter, 2000; Hayt and Buck, 2001; Maeda, 2004).

With a laser, which has a special value (or pulse) for its wavelength, the wavelength for LED is in spectrum width form. Therefore, the characteristics of LEDs cannot be distinguished from their wavelengths, since the energy is in a spectrum distribution form. Fig.7 shows the spectrum distribution for blue, yellow, and red LEDs (Maeda, 2004).

2. Experiment

As shown in Fig.3, a 1.55-μm laser source (LD) was used as the optical signal source for this experiment and emitted through the fabricated device.

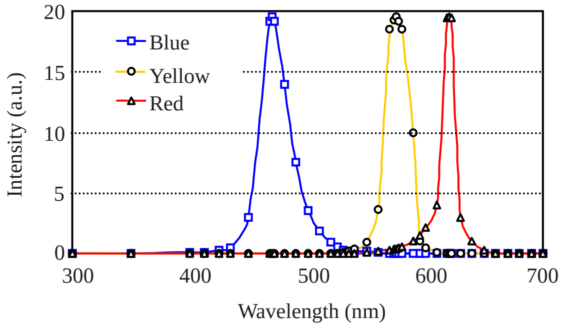

Fig.7 Energy spectrum for blue, yellow, and red LEDs

An IR pass filter was used to cut off any unwanted lighting (visible light, etc.). An IR polarizer acts to allow only either TE mode or TM mode to pass through it, so that the TE mode intensity (I_{TE}) and the TM mode intensity (I_{TM}) can be measured individually by the IR camera. The extinction ratio can be derived as $10\lg(I_{TM}/I_{TE})$ (dB).

Results showed that without any pumping light applied, the recorded extinction ratio was 4.60 dB. At the top of the device, three types of LEDs (blue, red, and yellow) were used as the pumping light. By changing the distance between pumping light sources and the device, the pumping light sources radiated onto the top of the device. The relationship between the radiation distance and the illumination for each LED is shown in Table 3.

Table 3 Relation between radiation distance and illumination

Distance (cm)	Illumination (lx)		
	Blue	Yellow	Red
1	87.6	440	110
3	73.5	360	86
5	67.5	321	76
10	51.0	238	60

The illumination values in Table 3 need to be transformed into a physical amount of energy, called the electrical power density. The relationship between the radiation distance and the electrical power density for each LED source is shown in Fig.8.

For radiation distances between 1 and 10 cm, each pumping light gave a different range of electrical power density. The blue LED gave the biggest range of values compared with the other two LEDs. Therefore, from Fig.8, the radiation distance and the current for each pumping source must be fixed so that the same electrical power density supplied to each LED could be obtained. The values of the fixed radiation distance and the current for each LED are shown in Table 4.

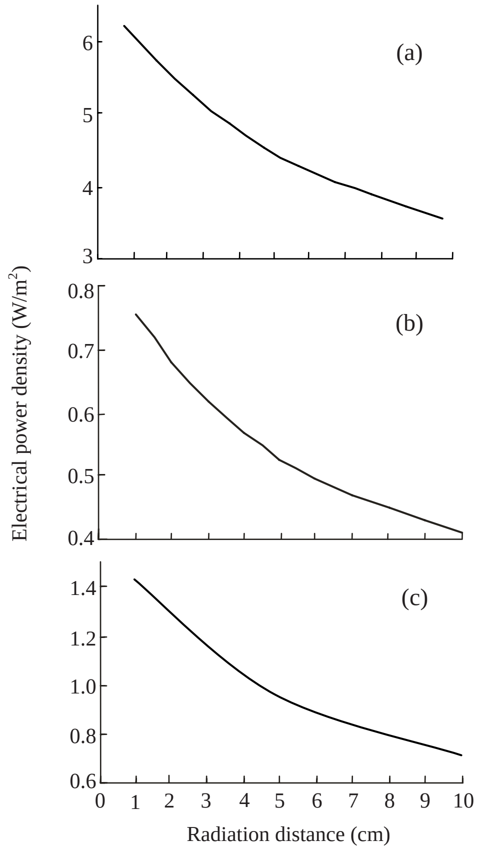

Fig.8 Electrical power density vs radiation distance
(a) Blue; (b) Yellow; (c) Red

Table 4 Radiation distance and current setting

Radiation distance (cm)			Current (mA)
Blue	Yellow	Red	
15	5	5	5
10	3	3	20
5	1	1	10

Based on Table 4, the relationship between electrical power density (W/m^2) and extinction ratio (dB) for each pumping light is shown in Fig.9.

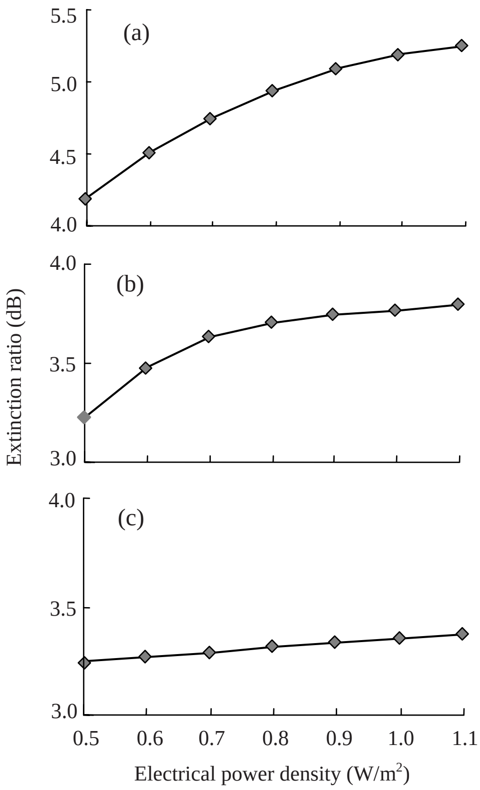

Fig.9 Electrical power density vs extinction ratio
(a) Blue; (b) Yellow; (c) Red

CONCLUSION

Based on the results from the fabrication process and the measurement of transmission characteristics using three different pumping lights, we may draw the following conclusions:

(1) A nanometer order fabrication process using DTCL-MPCVD equipment for an a-Si:H/SiN multilayer slab waveguide was successful.

(2) The characteristics analysis for this device, based on the results from Fig.9, shows that the extinction ratio for the blue LED is the highest compared with the other two LED sources.

(3) From Eq.(4), it was suggested that a light source with a wavelength lower than 560 nm gives the most effective result for the transmission process. Since the spectral distribution for the blue LED is between 400 and 550 nm, the results suggest that the blue LED will give a more effective transmission result (high extinction ratio) compared with the other two LEDs, red and yellow, whose spectrum distributions are 550~650 and 530~630 nm, respectively (Maeda, 2004).

(4) When the blue LED is used, its photon energy (which is below 560 nm) can pump or excite the a-Si:H electrons in the core of the waveguide, and by changing the electrical conductivity, the extinction ratio will increase (Kokubun, 1999).

(5) Electrons can be excited only at a certain wavelength, depending on the band gap energy of the materials used.

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