第 13 卷　第 4 期
2005 年 8 月

光学 精密工程
Optics and Precision Engineering

Vol. 13　No. 4
Aug. 2005

Article ID　1004-924X(2005)04-0492-08

A novel absorptive thin film for laser welding in optoelectronic device capsulation

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Abstract: A kind of absorptive thin film was designed and used in laser welding of SiO_2, Si and $LiNbO_3$. This absorptive thin film of three-layer metal-dielectric-metal structure is designed for further reducing the high reflectance of the Nd: YAG laser beam on the surface of the tin layer that is utilized as solder between the transparent parent materials. The actual absorption of laser energy in experiment exceeds 99 %. This combination of absorber and solder transformed the laser energy into heat efficiently and decreased the minimum necessary incident laser power transmitting through the transparent parent materials. As a result, the damage of the parent materials, which is suffered from laser transmission, was avoided; On the other hand, mechanical stability of the welded materials had been improved. Experiment had been made to show the difference between welding with and without the absorptive thin film.

Key words: absorber; absorptive thin films; laser welding; wave-guide; optical components; MEMS

1　Introduction

Laser welding is a kind of key technique in the field of optoelectronic device capsulation. This proved efficient technique is increasingly applied in the wave-guide materials such as SiO_2, Si, SiC and $LiNbO_3$. Our original suggestion is to joint the $LiNbO_3$ wave-guide and V-groove fiber optic assembly on the surface of the steel substrate. Generally, agglutination is the regular choice.

Actually, the correspondingly high expansion coefficient and short life span of the adhesives are the greatest drawbacks, though it is a convenient technique. Tin-copper and Tin-Indium joint technique is widely studied and proved to be an effective optoelectronic device bonding technique[1-3]. In these cases, the whole devices were put into the furnace tube and heated to the temperature of the melting point of the solders. The whole process lasted tens of minutes.

Cheng *et al* applied a nanosecond-pulsed laser lasing at 355 nm to implement glass-to-silicon bonding using a 4 μm thick indium layer as the bonding material[4]. In this case, the indium layer is deposited onto the silicon substrate in advance, then put a pyrex glass together with this substrate with the indium layer between the two materials. Laser beam transmits through the glass and reach the indium layer. Most of the UV laser energy is absorbed by the indium layer and transferred into heat. Given the proper laser energy, the indium is melted and joints the glass and silicon together. By using laser beam as heating means, the process duration is drop down to several milliseconds and the heating area is localized, which is more suitable to precision

Received date: 2005-06-06; **Revised date:** 2005-06-16.

finishing.

However, Nd: YAG lasers lasing at 1.06 μm are more commonly used in industrial laser welding. We purposed to bond the silica slice, LiNbO3 wave-guide and other optical components onto the steel or silica substrate, using the commercial Nd: YAG laser lasing at 1.06 μm. Differing from the 355 nm laser beam, the 1.06 μm laser beam suffers high reflecting on the most of the interface of metal and dielectric, which means low absorption of the energy in metal and that incident laser power could be high. High laser power leads high risk of cracking parent material as described in Fig. 1. In order to avoid the waste of laser energy, the breakage of welded material and to improve the safety control of operation as described in Fig. 2, we introduce a kind of absorber that can be used in laser welding.

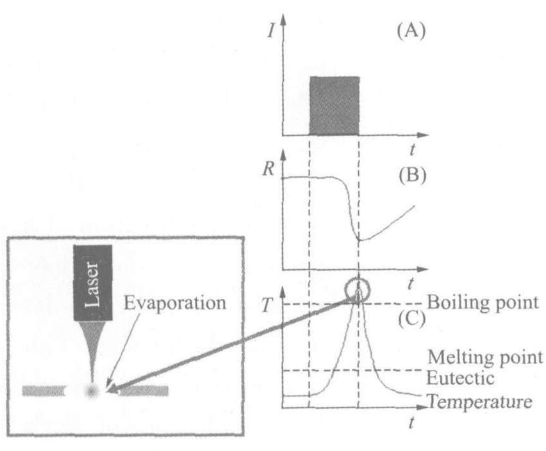


Fig. 1 High reflectance means energy lose & potential crack of parent material (A) laser intensity vs. time; (B) reflectance vs. time; (C) temperature vs. time

Absorber is widely used in solar energy collection[5], infrared and radiation absorption[6-7], stray light absorption etc. The absorber can be single layer of graphite, silicon (visible light range), metal-black coating, reflective-index-adaptable ceramic or optical interference thin films. In our case, several conditions should be matched:

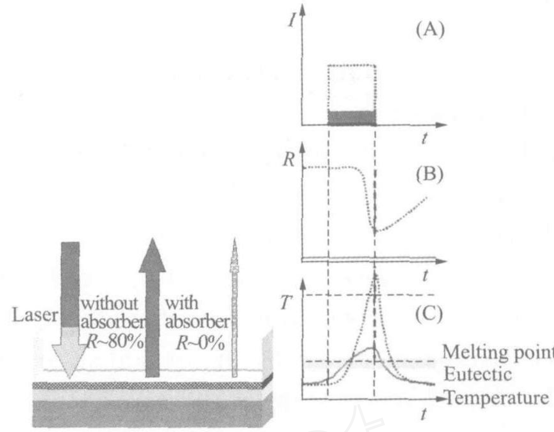


Fig. 2 Low reflectance means saving energy & low potential risk of cracking parent material (A) laser intensity vs. time; (B) reflectance vs. time; (C) temperature vs. time

(1) High absorption of 1.06 μm laser and easy to implement.

(2) Compact structure and high performance of firmness.

(3) Perfect adhesive ability with welding materials.

The metal-dielectric-metal structure we used, where metal stands for Ni or Cr, dielectric for SiO_2, can match the above conditions well for the reasons that Cr and Ni exhibit good adhesion with the glass and most of the metals[9] and that it can be conveniently designed by using diagram methods and interference matrix method. It can be deposited by electron beam evaporation to ensure high performance of firmness as well, which will be shown in detail in the following sections. The relevant experiments validated this effective functional film.

2 Absorber design

2.1 General description

In the research conducted by J. A. Dobrowolski et al, Modified Flip-Flop Method, Reflectance-Reducing Stack Method and Admittance Method were considered[9]. The Admittance Method is also introduced in Ref. 8 & 10.

In Addition, scattering formalism[7] and other methods, including what was used in Ref. 6, are also available. In this work, we adopted the Admittance Locus to design this absorber and then analyze the shift of the central wavelength through studying the reflectance spectrum of the absorber.

This absorber aims to highly absorb the 1.06 μm laser, which transmits through the upper transparent material. To provide an example, a metal-dielectric-metal structure of this absorber as Fig. 3 shows is studied. In practice, for the more convenient and accurate measurement of the optical constants of semitransparent Ni film[11], we used Ni film as the semitransparent layer of this absorber. However, in Ref. 11, only the optical constants at wavelengths ranging from 400 nm to 800 nm were provided, we utilized the similar method to attain the constants at near infrared wave range. The other metallic layer used is thick chromium film, which optical constants are more stable and close to those of the solid chromium. The thickness of this layer is tens of nanometers. Between these two metallic layers, there is a dielectric layer of SiO_2. The laser beam is reflected between these two metallic layers, and finally nearly attenuated to zero according to the exponential decay of light in the thick chromium film.

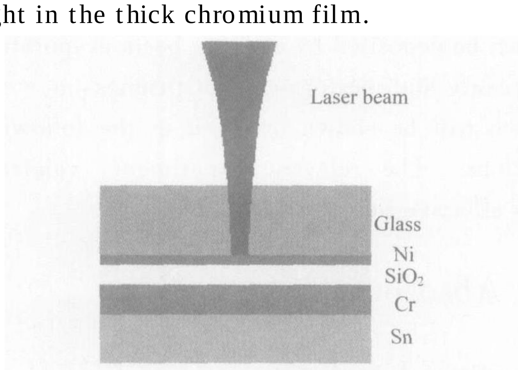


Fig. 3 Whole structure of the absorber

The glass substrate is 1mm thick. Transparent nickel thin film is first deposited onto the glass, followed by the SiO_2 layer and finally the thick chromium layer. The incident laser beam transmits through glass and is absorbed by the absorber. Heat generates in the absorber after absorbing the laser and transmits to the soldering material of tin.

2.2 Admittance locus and circle diagram

For this absorber, because the use of thick chromium layer acted as the bottom layer of the whole absorber structure, the transmittance is dramatically attenuated to nearly zero. According to the relationship of A, R and T:

$$A + T + R = 1 , \tag{1}$$

We can attain,

$$A \overset{T \to 0}{=} 1 - R \tag{2}$$

Therefore, where the reflectance is vanished, there is high absorption occurring.

According to the theory of the admittance locus presented by Macleod[12], the starting admittance Y_0 is the admittance of substrate, while in the layer structure we offered, the thick tin layer is the last layer along the direction of laser incidence. Theoretically, admittance diagram starts from the admittance of thick tin layer. However, considering that the incident light is nearly attenuated to none when the chromium layer is thick enough, the influence of thick tin film to the light is negligible and the starting admittance can be arbitrary. A simple treatment is to set the admittance starts from 1, which stands for the admittance of vacuum or atmosphere. The reference wavelength is 1.06 μm. Fig. 4 shows the admittance diagram of this structure. The admittance locus starts from the admittance of air Y_0 and ends at the admittance Y_E. The thickness of the nickel layer and SiO_2 layer is critical and should be chosen to meet the equivalency between Y_E and the admittance of the glass Y_G, which leads to the canceling of the reflectance.

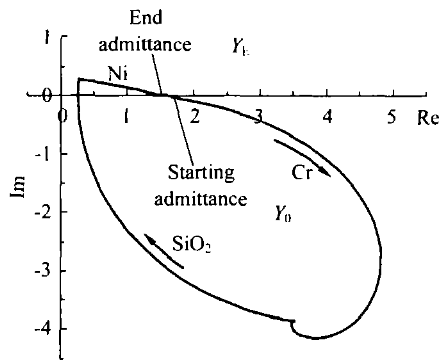


Fig. 4 Admittance diagram of the absorber

A more direct viewing of the performance is circle diagram, seeing Fig. 5. It reveals how the reflectance of the absorber varies as the deposit of the film is going on. As can be seen from the Fig. 5, the locus of the reflection coefficient ends at 0.0047 + 0.00676i and the reflectance attained is lower than 10^{-4}. The reflectance is extremely low, while the absorption is extremely high.

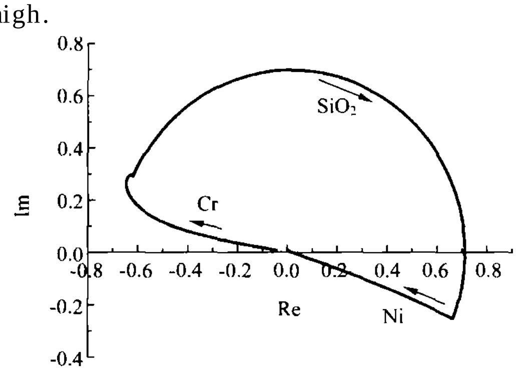
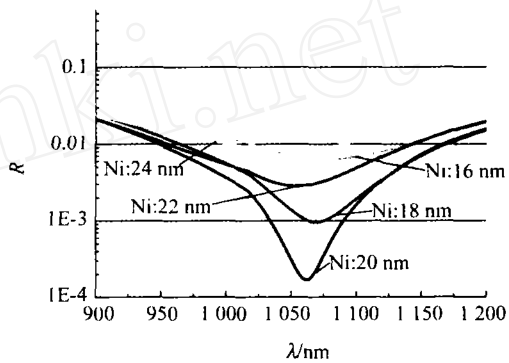


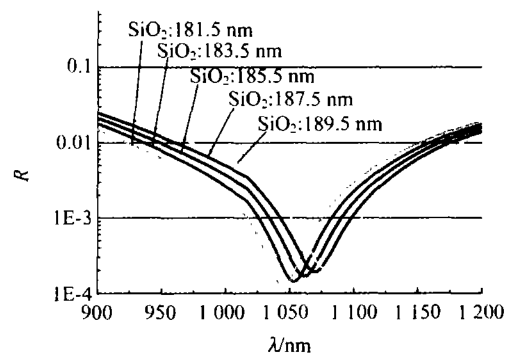
Fig. 5 Circle diagram of the absorber

2.3 Reflectance spectra and sensitivity analysis

In the above analysis, we only focused on single wavelength 1.06 μm, and we took the absorber as an ideal model and neglected the influence of the error generated during the film depositing. In practice, the center wavelength and the minimum reflectance are sensitive to thickness of the layers, especially the transparent nickel thin film. Calculate and draw the reflectance spectra, which is described in details in Ref. 12, can offer us the thorough data of the shift of central wavelength and the variation of the minimum reflectance. Fig. 6 (a) show the reflectance varies with the thickness of the transparent nickel thin film. From this figure, we can conclude that the deviation of the nickel thin film result in the shift of the central wavelength as well as the raise of the reflectance. When the thickness of the nickel thin film deviates from 20 nm to 16 nm or to 24 nm, the central wavelength experiences nearly 10 nm short



(a)



(b)

Fig. 6 (a) The thickness deviation of the nickel layer leads to the central wavelength shift and reflectance raise in the reflectance spectrum of the absorber; (b) while the thickness deviation of SiO_2 layer tends to influence the central wavelength most. The value marked for each curve manifest the thickness of the nickel or SiO_2 layer resulted from the thickness deviation.

shift or long shift and the reflectance at 1.06 μm raises from nearly 10^{-4} to nearly 10^{-2}. The similar phenomenon occurs with the deviation of thickness of SiO_2 layer which is shown in Fig. 6. (b), however, it does not behavior so sensitive as the nickel thin film does. So to speak, the thickness of the nickel thin film is the most critical factor.

In our case, the absorber is practicable when the reflection at 1.06 μm is lower than 0.01, for negligible little difference between the reflectance of 0.01 and 0, considering their influence to the absorptivity that is high up to 99 %. During the coating experiment, optical monitor were adopted and the accuracy will be well controlled in several nanometers, i.e., the precise control of the reflectance that should be lower than 0.01 at 1.06 μm is performable.

3 Experiment and results

3.1 Coating and film thickness monitor

The deposit of the film is accomplished by using DMDE 450 coater (Beijing Beiyi Chuangxin Vacuum Technology Ltd). The vacuum degree is set to 10^{-4} Pa. For the sake of precise thickness control, the deposit rate is set to 0.2 nm/s. Considering that the light is incident from the glass, the semi-transparent nickel thin film was first deposit on the glass, followed by the SiO_2 layer, and finally the thick chromium layer. In addition, a 1 μm thick tin layer was deposited next to the thick chromium layer for the purpose of welding. Optical and quartz crystal monitor were all used to monitor the film thickness. In practice, for this absorber was deposited on the glass in reverse order of the locus as the circle diagram described and the light was incident from the glass to the absorber, it was hard to monitor the reflectance directly by optical monitor technique. Transmittance monitor was alternative. We simulated how the transmittance varied as the film was being deposited. Referring to the method use in Ref. 11, the interference matrix is described as:

$$M_\nu \equiv \begin{pmatrix} \cos\delta_\nu & \frac{j}{\eta_\nu}\sin\delta_\nu \\ j\eta_\nu \sin\delta_\nu & \cos\delta_\nu \end{pmatrix}, \tag{3}$$

Where, $\delta_\nu = \frac{2\pi}{\lambda} n_\nu d_\nu \cos\theta_\nu$ is the phase-shift angle upon one traversal of the ν-th layer, η_ν represents the characteristic optical admittance of the ν-th layer.

The system interference matrix can be expressed as the multiple of the multiplying of the interference matrixes of different layers to:

$$M = \Pi M_\nu, \tag{4}$$

The transmittance T of the film can be deduced as shown in the following formulas:

$$\begin{pmatrix} B \\ C \end{pmatrix} = M \begin{pmatrix} 1 \\ \eta_s \end{pmatrix}, \tag{5}$$

$$T = \left(\frac{4\eta_0\eta_s}{(\eta_0 B + C)(\eta_0 B + C)^*} \right). \tag{6}$$

Where, η_0 is the admittance of the side where light is incident, η_s is the admittance of the substrate.

In our case, for the particular film deposit order, η_0 is the admittance of the glass, η_s is the admittance of the vacuum. As the new layer is deposited, the transmittance changes and can be calculated by using the formula (3)-(6). Therefore, a monitor curve, as shown in Fig. 7, is produced. By monitoring the fluctuation of the transmittance, the film thickness can be well controlled.

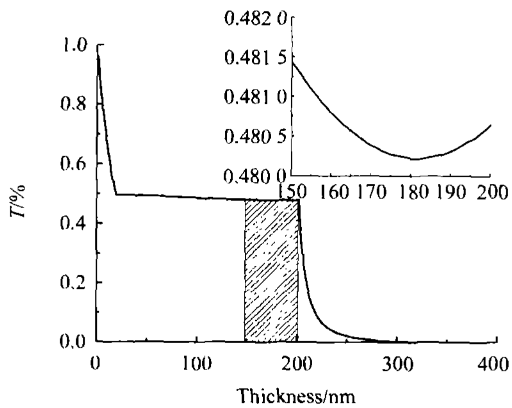


Fig. 7 Transmittance varies as the film is being deposited.

3.2 Results

Fig. 8 is a measured reflectance curve of the absorber. The minimum reflectance is lower than 0.01 at 1.06 μm though the central wavelength is shift to nearly 1 050 nm. One main error is supposed to derive from the thickness deviation of the SiO_2. As can be seen from the Fig. 7, when the thickness of the SiO_2 layer increases, the transmittance slides down to the valley tardily and climbs up a little, for the reason that the thickness of the SiO_2 layer is a little more than a quarter wavelength. In addition, the monitor accuracy is relatively lower. On the other hand, the nickel thin film could be deposited excessively. Therefore, the central wavelength deviated resulting from the monitor error. However, as the analysis presented in sector 2.3, the thickness deviation of SiO_2 is more likely to influence the shift of central wavelength than the minimum reflectance, while that of the nickel layer is opposite.

To identify the performance and effectiveness of the absorber in laser welding, a contrastive experiment was implemented. We prepared two kinds of thin film specimens, which were all deposited on the glass substrates. For one, named #1, it was only a 1μm thick tin layer deposited, which acted as welding material. Fig. 9 shows the layer structure, in the structure, the thin chromium layer is transition layer and several nanometers thick. For the other, named #2, the absorber and a 1 μm thick tin layer were deposited sequentially. Fig. 3 shows the thorough structure.

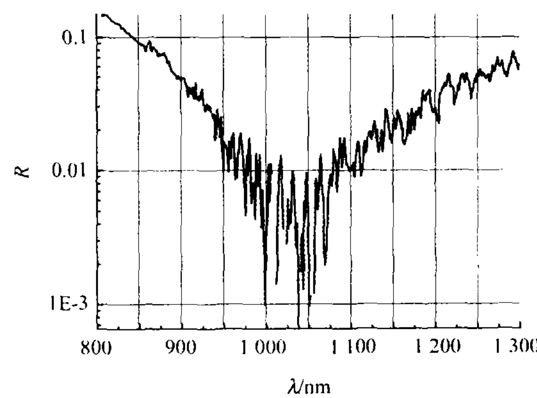


Fig. 8 Reflectance spectra of the absorber. The wavelength ranges from 400 to 1 500 nm

Fig. 9 #1 specimen Chromium and tin film are deposited sequentially on glass substrate.

The basic setup for the laser bonding is the so-called transmission welding principle. As we can see from the Fig. 10, laser transmits through the transparent material, such as glass, and is finally absorbed by the welding material, while a small part of the laser is due to absorption in the transparent material. In this case, laser is an efficient way to heat up the welding material. Before the welding process, the glass plates #1 or #2 should be put together with the welding layers facing opposite. For the sake of close contact of the two surfaces, these two plates were pressed together, avoiding cracking the glass plates. A W-50 laser welder, produced by Hanslaser, is applied to welding process. The working wavelength is 1.06 μm and the maximum laser output is 60 W.

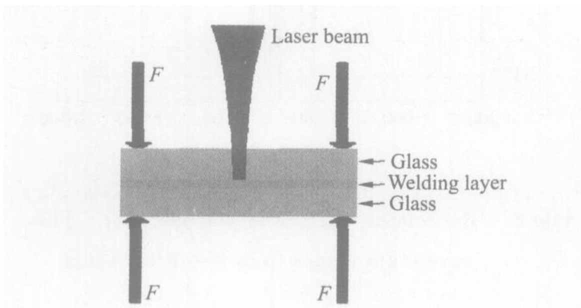


Fig. 10 Schematic diagram of the welding process

During welding the #1 and #2 specimens, the same pulse duration was set to 1 ms, while the minimum pulse energy required and the area of the welding zone varied. For #1 specimen, the minimum laser pulse energy was 0.8 J and the area of welding zone is 1.9711 mm^2; for #2 specimen, the minimum laser pulse energy was 0.5 J and the area of welding zone is 4.5216 mm^2. The ratio of the power density of #1 and #2 is 3.67. The utilization factor of laser energy was improved in #2 specimen. Considering the loss due to the absorption of chromium transition layer and the reflectance of the tin interface, no more than 40% laser energy was absorbed by tin layer in #1 specimen. On the contrary, more than 99% laser energy was absorbed by the absorber in #2 specimen. Supposed that the welding layer involves high reflectance metal layer such as Cu, the utilization factor could be more remarkable.

4 Conclusion

The metal-dielectric-metal structure absorber is utilized in the transparent material nondestructive transmission welding, and the design and implementation were described and explained. By using this absorber, the reflectance of the welding layer surface is dramatically reduced. As a result, the utilization coefficient of laser energy is maximized for the high absorption. Therefore, the minimum necessary incident laser power is decreased into a low level, which avoids the potential risk of the damage of the transparent materials when the laser beam transmits through them. In the future work, this absorber will be further studied and used in the optical components laser welding.

5 Acknowledgemetns

This research was greatly supported by Hanslaser Ltd. The experiment was carried out fluently with the support of the welding equipments provided by Hanslaser and the kind effort of the engineers in Hanslaser. This research was supported by Hanslaser Ltd, National 863 (2003AA311022) Project of China and National 973 (2003CB314901) Project of China.

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