Study on 55°, 905 nm, high reflectivity and visible range beam splitter in cemented cube

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Received November 12, 2012; accepted January 7, 2013; posted online June 14, 2013

This is a difficult kind of beam splitter in a cemented cube. The specification is: under angle of incidence (AOI)= 55°, the reflectivity at 905 nm is no less than 85%, and in the visible range the average transmittance is 40±2%, and $T+R\geqslant 90\%$. Because the AOI is 55°, it needs to use a metal coating material to make sure the film be designed. The film has some problems on durability, and its optical performance is very hard to be controlled. We get some experiments after changing its design including coating material and evaporation technique. Final results show that the beam splitter has good properties, and passed temperature, and environmental durability.

OCIS codes: 230.1360, 310.3915.

doi: 10.3788/COL201311.S10407.

Along with the rapid development of the physical science and the information industry, the performance of the modern optoelectronic products and instrument are more and more advanced, with more and more functions. Miniaturization and light-duty are its development trend. Beam splitter is one of the most important components in order to realize miniaturization and light-duty in photoelectronic instrument. In order to ensure the capability of photo-electronic system which combines visible wave band (450−656 nm) and laser wave band (905 nm) in one body, it must coat a film with visible area beam-splitting ($T_{\rm ave}$=40±2%, $T+R\geqslant 90\%$), and high reflection ($R\geqslant 85\%$) in laser band.

Since the angle of incidence (AOI) is wide (55°), and the substrate is cemented prism, the coating system is very difficult to design with dielectric material. The product needs to pass the environmental test such as low temperature test, hot and humid test, etc., which require higher film quality. This letter introduces the method of making the beam-splitters by combination of metal film and dielectric film, and introduces some researches from coating design to coating technology. Finally, the coating can meets the actual requirements.

The substrate is prism glass BaK7, and after cemented. The specification is as follows: AOI= 55°; λ_{01}=450–656 nm; $T_{\rm ave}$=40±2%; λ_{02}=905 nm; $R\geqslant 85\%$.

The coating system is very difficult to design with dielectric material, because the AOI=55°. We design the coating with combination of metal film and dielectric film.

The beam-splitter requires low absorption, so the metal material with larger k/n value has better performance in the coating system. In the visible region, silver film has the lowest absorption[1]. Therefore, we decided to use Ag as metal material in the beam-splitter design.

The formation of the metal film began in nucleation. After nucleation, film growth process will experience island stage, coalescence stage, ditch stage, and continuous stage[2]. As shown in Fig. 1, the film in island stage of also called discontinuous film or half continuous metal film[3,4]. As increase of the deposition thickness, the film transits from separating island to the network, continuous state gradually, finally stables in the continuous state.

Because half continuous metal film has different structure from the continuous metal film, it has different optical and electrical properties, which used widely in microelectronics and optoelectronics and various functional materials[5,6].

By South Korea Univac 1 200 vacuum coating machine, we plate 25-nm Ag film (island structure) and 600-nm Ag film (continuous structure) on BaK7 substrate, then measure the transmittance by Perkin Elmer Lambda 1 050 spectrophotometer, as shown in Figs. 2 and 3.

From Figs. 2 and 3, we can see that two Ag films have different optical performance. In the visible region, thicker continuous Ag film has very low transmittance, and half continuous Ag film has higher transmittance. The absorption of metal film not only depends on the optical constant of metal film itself, but also admittance of its adjacent dielectric

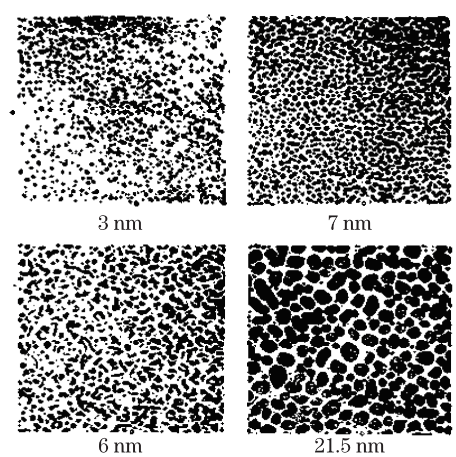

Fig. 1. Different thickness Ag film island structure electron micrograph.

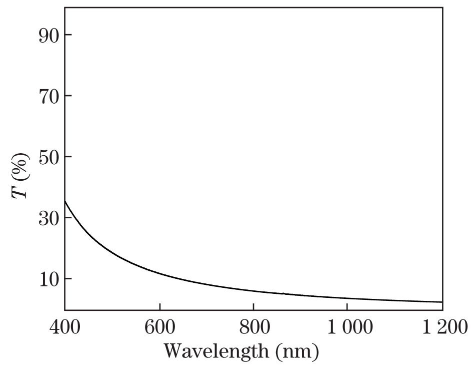

Fig. 2. 25-nm silver film transmittance.

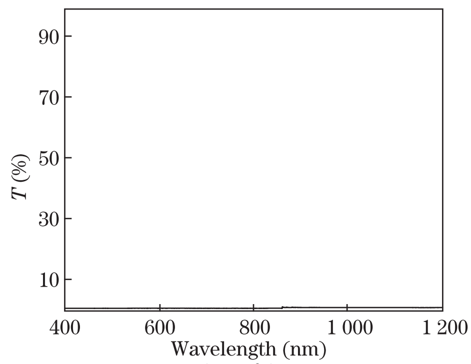

Fig. 3. 600-nm silver film transmittance.

layers. The transmittance of the film will become the largest, as long as choose the correct admittance of the film on substrate side. If design anti-reflection (AR) film on the incident side, it can develop the largest possible transmittance of the metal film, this is the induced-transmission concept[1]. We can use half continuous Ag film's optical properties and induced-transmission principle for the design of the beam-splitter.

We measure half continuous Ag film by ellipsometer, then get thickness and optical constants. In single layer film system, it composed by air, film, and substrate. Import elliptic partial parameters ψ and Δ, it is

$$\mathrm{tg}\psi e^{\mathrm{i}\Delta} = \frac{\rho_{1\mathrm{p}} + \rho_{2\mathrm{p}} e{-}\mathrm{i}2\delta}{1 + \rho_{1\mathrm{p}} + \rho_{2\mathrm{p}} e{-}\mathrm{i}2\delta} \times 1 + \rho_{1\mathrm{s}} + \rho_{2\mathrm{s}} e{-}\mathrm{i}2\delta$$
$$\rho_{1\mathrm{s}} + \rho_{2\mathrm{s}} e{-}\mathrm{i}2\delta = f(n_0,\, n_\mathrm{f},\, n_\mathrm{s},\, \varphi_0,\, t,\, \lambda), \quad (1)$$

where n_0, n_f, and n_s are the refractive index of air, film, and substrate, respectively; ϕ_0 is the AOI, t is film the thickness; $\rho_{1\mathrm{p}}$ and $\rho_{1\mathrm{s}}$ are the air-film interface reflectance, $\rho_{2\mathrm{p}}$ and $\rho_{2\mathrm{s}}$ are the film-substrate interface reflectance; 2δ is the optical thickness of the thin film.

Generally n_0, n_s, ϕ_0, and λ are known. Ag film have absorption, n_f is complex refractive index, $n_\mathrm{f}{=}n{+}\mathrm{i}k$ (n and k are refractive index and extinction coefficient of the thin film). In this equation are three variable t, k, n, as long as measure three different ϕ_0 of elliptic partial parameters ψ, Δ with wavelength λ change, we can calculate the thin film optical constant and film thickness. Read Ag film optical constant in design software, carry on the film design.

The adhesion of Ag film is poor. In some special atmosphere the Ag film is easy to be corrode and fall off, which affect the performance. In the experiment we discovered that join transition layer can improve Ag layer's firm degrees[7].

The original film structure is

$$G|(LH)MAM(HL)|G, \quad (2)$$

where G is the glass substrate, H is the high refractive index dielectric film materials, L is the low refractive index dielectric film materials, M is the transition layer, and A is Ag film. Limit the physics thickness of 20−60 nm.

Design the film by Needle method in TFC software, find out the best film system. Theory design get curve as shown in Fig. 4.

Coat the film on Univac 1 200 vacuum coating machine made from South Korea which control thickness and rate by quartz crystal monitoring meter and equip End-Holl ion source. In the coating process, there are two difficulties: 1) How to improve the Ag layer adhesion; 2) how to solve the problems that the optical performance is difficult to control.

Film adhesion comes from the interaction between layers. There are two kinds of film adhesion: physical adsorption and chemical adsorption. Physical adsorption mainly equals the total of Van Der Waals force, dipole effect, induced effect and Lorentz force. Chemical adsorption has several types as follow: 1) Adhesion from which two adjacent material produce chemical reaction. After chemical reaction two materials generate a certain components of compound which connect the two materials. In the interface of two materials there is not only chemical reaction from two materials directly, but also connection of these two kinds of material by the third kind of material. 2) Adhesion caused by diffusion. When contact, two kinds of material diffusion their atoms to each other because of the concentration gradient, which will inevitably lead to the acting forces between atoms. The diffusion capacity depends on material and temperature, and so on. 3) Adhesion caused by propinquity diffusion. It is not diffusion above, but the propinquity diffusion which happen when the atom with big kinetic energy impact the film and enter it.

Chemical adsorption caused by chemical reaction or mutual deep penetration, the adhesion is much larger than physical adsorption.

To improve adhesion, we mainly adopted the following methods. 1) Select Al_2O_3 as transition layer material. Reference [8] pointed out that, because Al and Ag have small difference on electric negative, atoms are easy to diffusion and penetration. Ag atoms permeate into the Al_2O_3 layer, Al atom and a small amount of O atom permeate into the Ag layer, which forms chemical adsorption. 2) Improve substrate clearness. Before coating etch substrate for 5 min with ion source, which can remove water vapor, dirt and other adsorbate on the substrate, and can improve the film adhesion. 3) Choose appropriate substrate temperature. The appropriate substrate temperature can not only get rid of substrate surface residual gas and various kinds of solvents, but also conducive to film layer atomic mutual diffusion, which is beneficial to the forming diffusion adsorption. But high substrate temperature will increase the absorption of silver layer. Through the experiment, when the substrate temperature is 80 °C, the film absorption is small, and the film has good adhesion. 4) Coat transition layer with

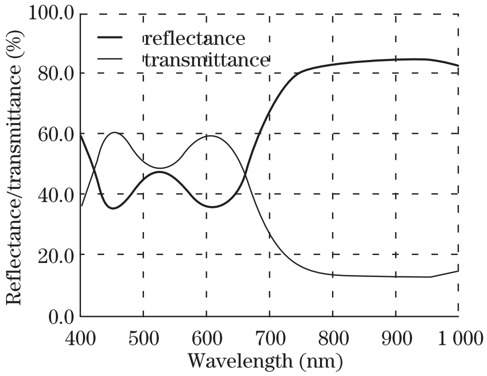

Fig. 4. Theoretically design.

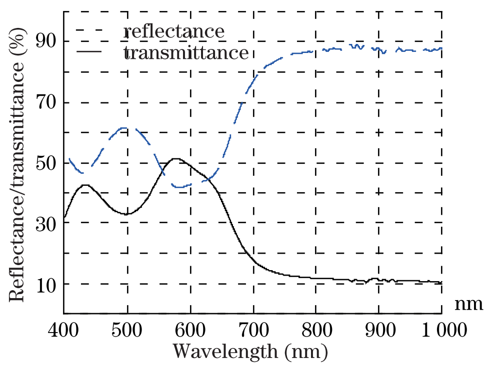

Fig. 5. Measurement results.

ion source assisted. In the coating process of transition layer, ion source can provide atomic larger kinetic energy, which increases the probability of propinquity diffusion and improve the film adhesion.

In the experiment, it is hard to get stable film optical performance, and film optical performance has poor repeatability. In order to solve this problem, mainly in the following two aspects to take measures: 1) the film optical performance is very sensitive to the thickness of half continuous Ag layer, and the slight change of the Ag film thickness will bring optical performance obvious change. So take curing measures of Ag coating process control, and strictly control the coating thickness. 2) The film absorption will bring optical performance obvious influence. Due to the absorption of metal film not only depends on the optical constant of metal film itself, and also is related to the adjacent dielectric admittance closely[1]. So to make the film optical performance stable, the dielectric film admittance which is matched the metal film must be stable. Control substrate temperature, deposited rate and pressure in the vacuum chamber and so on parameters in the coating process to ensure dielectric film admittance stable.

Measure with the Hitachi 4100 spectrophotometer, and the measurement results are shown in Fig. 5.

We did adhesion test according to MIL-C-48497. Pressed 3M tape on the coating surface firmly, then quickly removed it. No coating had been found to be peeled off on the tape. After abrasion for 50 times, the coating had not been found to be broken. We also make the environmental test, test index is as follows: 1) Hot and humid test: in temperature 40±2 °C, relative humidity 90%−95% of the conditions keep 24 h, film do not fall off, optical performance meet the requirements; 2) low temperature test: in −40±3 °C low temperature keep 2 h, film do not fall off, optical performance meet the requirements.

In conclusion, the 55° incident beams-splitter can be designed with the combination of metal film and dielectric film by taking use of half continuous Ag layer optical performance and induced-transmission principle. The transition layer can effectively improve the film adhesion. In the coating process, take measures as much as possible to realize the chemical adsorption, which can improve the adhesion. Precise control of the Ag layer thickness and adjacent dielectric layer admittance can effectively guarantee repeatability of the film optical performance repeatability.

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