Experimental study of sweep control in e-beam evaporated optical coatings

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High performance optical coating requires excellent uniformity of thin-film. Keeping the surface of evaporation material flat is propitious for the stability of vapor plume, and can improve the uniformity of thin-film. Based on the principle of electron beam spot sweep, a pattern controller in domestic coater is designed. For the purpose of even evaporation during auto-sweep, the influence of the depth of material surface in the crucible on the evaporation characteristic is considered. Pre-melting and evaporation experiments are performed on melting material (Ti_3O_5), subliming material (SiO_2), and semi-melting, semi-subliming material (HfO_2). The sweeping experimental results show that using the designed sweep controller can make good performance on evaporation and pre-melting for the above materials.

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Electron beam (e-beam) vacuum evaporation deposition is extensively used to manufacture multi-layer optical coatings[1−3]. High precision coatings in advanced optical systems require excellent process control capability for e-beam evaporation systems[4]. However, for most domestic coaters, the process control capability is limited by the stable deposition rate control and uniform beam sweep over the evaporation material surface. Deposition rate control and e-beam sweep pattern have been identified as two critical aspects that can be optimized to significantly reduce the process variations leading to coating performance errors[5]. Sweep pattern, if not designed appropriately, can have great influence on the deposition rate. Sweep patterns can be in theory designed with the objective of maintaining the uniform rate and keeping the melt surface flat[4]. In this letter, automatic sweep pattern in domestic coater is designed based on the principle of e-beam spot sweep. Using the designed sweep controller, evaporation, and pre-melting experiments are performed on different thermal property materials including Ti_3O_5, SiO_2, and HfO_2. The experimental results show that using the designed sweep controller can make good performance on the evaporation and pre-melting for the above materials.

A sweep controller is always used to generate the currents driving the electro-magnetic coils to swing the beam. Programmable sweep controllers use a set of discrete points with adjustable dwelling times to define a sweep pattern for better beam energy distribution over the source surface. From the sweep design point of view, it is desirable to uniformly heat and evaporate the material to maintain a flat surface and the maximum material utilization[6−9].

For materials of good thermal conductivity, the heat of beam can spread in a short time, and the deposition rate rises to a stable rate rapidly[10]. So the beam spot dwells a short time at the same melt position during sweeping. For materials of poor thermal conductivity, the deposition rate rises slowly, and it takes longer time to reach stable rate[10], so during sweeping, the beam spot stays at one melt position for a longer time on materials of poor thermal conductivity than that on materials of good thermal conductivity. The distance from melt position to the next one is designed as short as possible to reduce the effect of temperature decrease of heated area. The dwelling time at one melt position is calculated according to the heat distribution of e-beam spot of focusing characteristics.

A sweep controller is designed to achieve the above purposes, which is composed of signal amplifier, function selector, and voltage follower, and is connected to two electro-magnetic coils, a manual controller, and a computer. The connection of instruments is shown in Fig. 1. The computer designs the sweep pattern, and sends control signals to the sweep controller through a data acquisition card. The sweep controller amplifies signals and generates control currents, and then uses them to driving electro-magnetic coils. The sweep control panel is shown in Fig. 2.

As shown in Fig. 2, the sweep pattern is composed of a series of points, which represent the positions of evaporation spot in the crucible. Each point of sweep pattern is determined by the voltages of X-magnetic coil and Y-magnetic coil, so the sweep pattern can be presented by the voltages $V(V_{\mathrm{control}Xk}, V_{\mathrm{control}Yk})$ and the overall

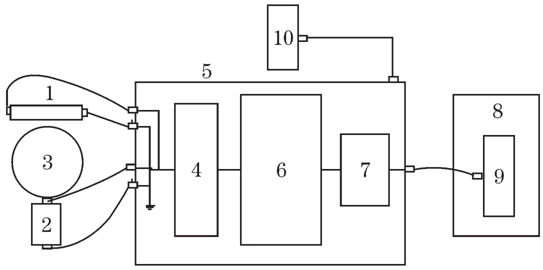


Fig. 1. Connection of instruments.

1: X-magnetic coil, 2: Y-magnetic coil, 3: crucible, 4: signal amplifier, 5: sweep controller, 6: function selector, 7: voltage follower, 8: computer, 9: data acquisition card, 10: manual controller.

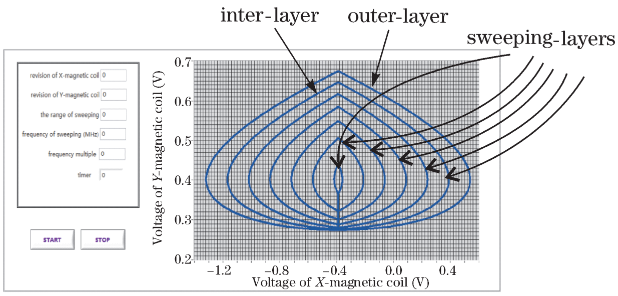


Fig. 2. Sweep control panel.

sweep patterns can be regarded as a $2\times k$ array.

The parameter ‘frequency of sweeping’ is the frequency of one point of sweep pattern moving to the neighboring point. Choosing proper sweep frequency according to different evaporation characteristics of different materials, the front of material can be kept as flat as possible, which can reduce the influence of surface topography on the vapor plume shape. The ‘frequency of sweeping’ is set as the frequency of the innermost layer, and expressed as Frq_{basic}.

The focus characteristic of e-beam in the central area of crucible is better than that of e-beam in the outer area of crucible. So when sweeping, the ‘frequency multiple’ is set according to the sweeping area of crucible and expressed as Frq_{multi},where Frq_{multi} is concerned with the number of sweeping layer. If there are m layers in the sweep pattern and the sweep begins from the innermost layer, the actual sweep frequency of the nth layer is Frq_{actual}, expressed as $Frq_{\text{actual}} = Frq_{\text{basic}}/(Frq_{\text{multi}}\cdot n)$, $1 \leq n \leq m$.

With the evaporation of material, the material surface will subside, and for this reason, the evaporation spot on the material surface will change. As shown in Fig. 3(a), when e-beam hits the material surface, there is an angle between the incidence direction of e-beam and the normal direction of material surface, which is shown in the trace C. If the magnetic field intensity of Y-magnetic coil does not change, the e-beam along the trace C focuses at point J_A on the surface A and at point J_B on the surface B, which is h deeper than surface A. There is a displacement S between J_A and J_B on the Y-axis direction, so the part of sweep pattern of the surface B will hit the crucible, as shown in the surface B'. The surface B' cannot cover the evaporation flat, and the e-beam will hit the crucible.

For the purpose of focusing the e-beam on the surface B, the deflection radius of e-beam trace of every point on sweep pattern must be adjusted to avoid the e-beam hitting the crucible. As shown in Fig. 3(b), the deflection radius of the e-beam changes with the varying of the magnetic field intensity of Y-magnetic coil, so the control voltages of Y-magnetic coil must change with the varying of depth h of material sedimentation. The changing magnitude of the control voltage of Y-magnetic coil corresponding to the material sedimentation depth can be determined experimentally. The ‘voltage revision of Y-magnetic coil’ in Fig. 2 is the changing magnitude of the control voltage of Y-magnetic coil for the e-beam sweeping the whole evaporation source material every time.

There are three kinds of materials in the experiments: ‘melting materials’, ‘subliming materials’, and ‘semi-melting, semi-subliming materials’. The melting materials have good thermal conductivity, and can be kept in liquid state during evaporating. The evaporation of semi-melting, semi-subliming materials is more difficult than melting materials, and the melt fronts are rougher than melting materials. The subliming materials with good thermal conductivity are hard to evaporate. Ti_3O_5, SiO_2, and HfO_2 materials are selected in experiment.

For instance, SiO_2 is a kind of typical subliming material[10], and for the purpose of getting flat melting front, three experiments on evaporation of SiO_2 are performed and compared. The parameters of SiO_2 experiments are shown in Table 1. The results of SiO_2 experiments are shown in Fig. 4. As shown in Fig. 4, SiO_2 has the flattest melting front in the third experiment. The melting front of experiment 1 has an obvious apophysis in the center. The melting front of experiment 2 is flatter than 1, but still has an apophysis

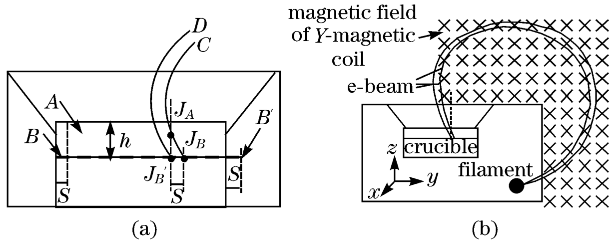
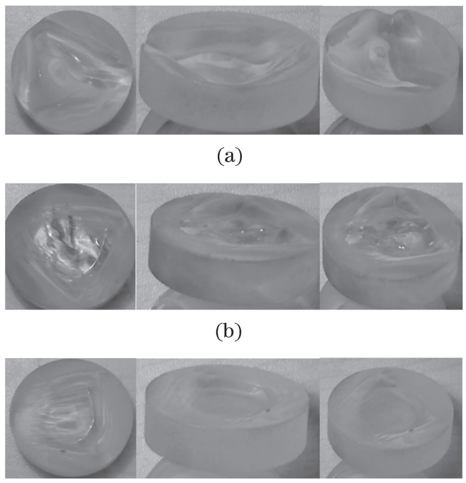


Fig. 3. (a) E-beam trace in crucible and (b) deflection of e-beam in the magnetic field of Y-magnetic coil.

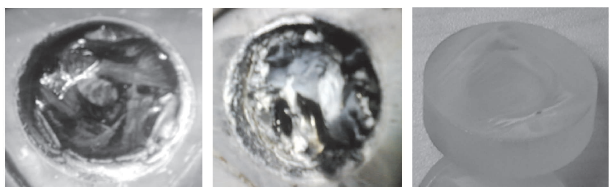


(a)

(b)

(c)

Fig. 4. Results of SiO_2 experiments. (a)−(c) correspond to the SiO_2 experiments 1 − 3, respectively.



(a) (b) (c)

Fig. 5. (a) Pre-melting of TiO_2+Ta_2O_5, (b) pre-melting of HfO_2, and (c) evaporation of SiO_2.

Table 1. Parameters of SiO_2 Experiments

No	1	2	3
Current of E-Beam (mA)	50−100	50−60	50−80
Frequency of Sweeping (Frq_{basic}) (Hz)	50	25−50	25−50
Frequency Multiple	2.5−3	2.5−3	1.5−2.5
Voltage Revision of Y-Magnetic Coil (V)	0.05	0.03	0.04

Table 2. Parameters of Experiments for Different Materials

Material	HfO_2	Ti_3O_5	$Ta_2O_5+TiO_2$(3:7)
Current of E-Beam (mA)	180−200	60	150
Frequency of Sweeping (Frq_{basic}) (Hz)	30−60	150	80−150
Frequency Multiple	2−3.5	1.5	1.2−1.5
Voltage Revision of Y-Magnetic Coil (V)	0.05	0.02	0.02

in the center. The differences in the melt front of these three experiments are due to the differences in sweeping speed of different layers and the integral variation of control voltage of Y-magnetic coil during material evaporating. Adjusting the parameters of frequency of sweeping, the voltage revision of Y-magnetic coil, and the frequency multiple, the melting front of material can be improved, as shown in Fig. 4(c).

The experiments are performed on different materials, and have better performance with the parameters shown in Table 2. The results of the experiments are presented as follow.

1) The melting materials Ti_3O_5 and $TiO_2+Ta_2O_5$(3:7) are used in experiments. The results on evaporation and pre-melting are all good. The picture of pre-melting of $TiO_2+Ta_2O_5$ is shown in Fig. 5(a). The melting area covers more than 95% of the crucible surface and the melting front is flat. 2) The 'semi-melting, semi-subliming material' HfO_2 is used in experiments. The picture of prep-melting of HfO_2 is shown in Fig. 5(b). The melting area covers more than 75% of the crucible surface and the melting front is flat. 3) The 'subliming materials' SiO_2 is used in experiments. The picture of evaporation of SiO_2 is shown in Fig. 5(c). The surface front after evaporation is also flat.

In conclusion, the designed sweep controller can use different sweep patterns to evaporate and pre-melt materials of different heat conductivities. The design of sweep pattern considers both the depth of melting surface in the crucible and the sweep frequency of different materials. When the depth of melting surface is changing, the integral variation of control voltage of Y-magnetic coil is changing according to the physical characteristic of evaporation material. For 'melting material', the sweeping frequency can reach $80 - 100$ Hz and the frequency multiple can be $1.2 - 1.5$. For the pre-melting and evaporation of 'semi-melting, semi-subliming material', the sweeping frequency of $50 - 100$ Hz and the frequency multiple of $1.5 - 2$ can achieve a good performance. For the 'subliming material', the lower sweeping frequency and frequency multiple can help the sweeping to make a better performance. The efficacious sweeping frequency is lower than 50 Hz and the frequency multiple can be $1.5 - 2.5$. The results of experiments show that using the designed sweep controller can make good performance on the evaporation of all 'melting materials', and on the pre-melting of granular materials ('melting materials' and 'semi-melting, semi-subliming materials' only).

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