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Enhanced interference using microcavity structure for accurate thin film thickness measurement

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A new method based on microcavity structure is developed for accurately measuring the thickness of organic thin films. By sandwiching the thin films between a bottom reflective mirror and a top semi-reflective mirror, the interference effect is greatly enhanced. As a result, the reflectance spectra exhibit distinctive, strong, and sharp interference peaks. The interference pattern is very sensitive to the thickness of the thin films. By fitting the interference pattern with the calculated reflectance spectra, the thickness of the thin films can be accurately determined.

1 Introduction Thickness, as one of the important parameters of thin films, determines many aspects such as optical, electrical, and mechanical properties of thin films, and affects the performance of related devices. It is, therefore, necessary to accurately measure the thickness of thin films. Among various measurement methods, stylus profilometry [1] is the most common technique which detects the profile of samples and thus measures the thickness by calculating two planes height difference. However, accuracy of stylus profilometry remains an issue, and the problem becomes even worse when measuring thin and soft films like organic samples, as the soft films are easy to be damaged by the stylus. To remedy this issue, nondestructive methods based on optical techniques such as interferometry are employed [2, 3]. The interferometry measures the spectral reflectance of the samples and, therefore, requires the films have moderate reflectance. To measure transparent samples like organic and dielectric, the films are generally deposited on reflective substrate so that moderate reflectance can be detected, as shown in Fig. 1(a). In such configuration, the incident light is reflected by the top and the bottom interface of the films. The total amount of reflected light is the sum of these two individual reflections. If the reflections from the two interfaces are in phase, then they add constructively and otherwise destructively. The phase is determined by the optical path lengths which in turn is determined by the thickness of the films, its optical constants, and the wavelength of the light. For light perpendicularly incident on a sample, if the thickness of the film d satisfies: $2Nd = i\lambda$, where N is the optical constants of the film and i is an integer, then the reflections at point A and B are in phase and they add constructively. Conversely, reflections are out of phase and add destructively if $2Nd = (i + 1/2)\lambda$. Therefore, the interference pattern is closely related to the thickness of the film. If the optical constants of each material are known, then the spectral reflectance can be calculated by using transfer matrix method [4]. By measuring the reflectance and fitting the interference pattern with the calculated data, the thickness of the film can be extracted. Stronger interference generates sharper interference peaks and thus makes the fitting easier and more accurate. Since the interference is the sum of the reflections from the top and the bottom interface, both top and bottom interfaces thus should have moderate reflection to generate sharp interference peaks. However, in the conventional method as shown in Fig. 1(a), the reflection at the top interface of transparent films is quite low, which results in a weak interference and thus makes the fitting difficult and inaccurate.

In this work, a semi-reflective top mirror is introduced to increase the reflection of the top interface of the film and thus enhance the interference. As shown in Fig. 1(b), the film is sandwiched between a reflective bottom mirror and a

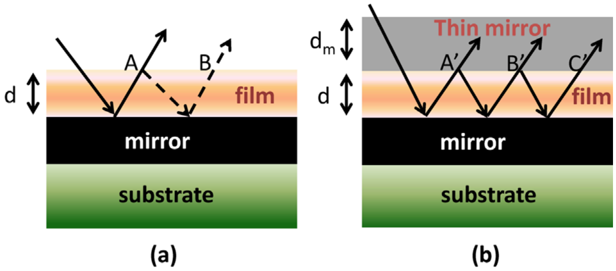

Figure 1 Schematic illustration of (a) conventional structure and (b) proposed microcavity structure used for measuring the thickness of thin films.

semi-reflective top mirror. The resultant structure is very similar to a microcavity structure, which is commonly used to enhance the color saturation of organic light-emitting diodes [5, 6]. Due to strong interference induced by the reflection of the mirrors, the reflectance spectra of the structure exhibit very sharp interference peaks. The interference pattern is highly sensitive to the thickness of the film. By fitting the interference pattern with the calculated data, the thickness of the film can be accurately extracted. The developed method, only involving measurement of reflectance spectra using spectrometer, is simple, low cost, and particularly useful for accurately measuring the thickness of transparent and soft organic thin films.

2 Results and discussion

The samples are prepared using thermal evaporator. A 100 nm thick Ag film was first deposited on the substrate as bottom mirror to provide reflection for the transparent organic thin films, followed by depositing an Alq film with different thickness for testing. For the samples with microcavity structure (Fig. 1(b)), a 20 nm thick Ag film was further deposited on top of Alq as top semi-reflective mirror. The reflectance spectra at normal direction were measured by using an Ocean Optics USB 2000 spectrometer and a visible light source, as schematically shown in Fig. 2. The reflectance spectra were calculated by using the transfer matrix method [4]. The n, k values of Ag and Alq can be found in the Supporting Information (online at:

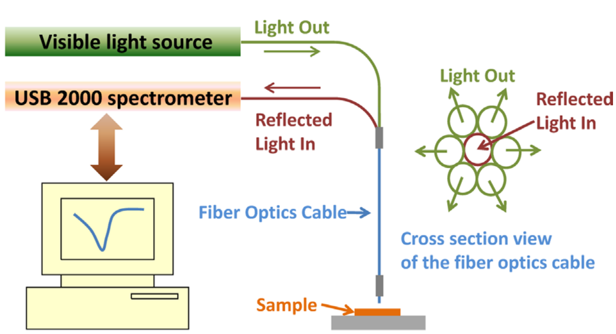

Figure 2 The experimental setup used to measure the reflectance spectra of the samples.

www.pss-a.com). By fitting the measured reflectance with the calculated data, the thickness of the organic thin films d and the top mirror d_m can be extracted. To further verify the fitting results, the thickness of the organic layer is measured by a Dektak 150 Veeco surface profiler.

The transfer matrix method is employed in optics to analyze the propagation of electromagnetic through a stratified medium [4]. Stratified structures contain isotropic and homogeneous medium and every interface can be regarded as parallel plane. The light incident to the device is described as a plane wave. For each layer, its complex index of refraction is $Ni = n_i + i\kappa_i$. Here the real part n is the refractive index, while the imaginary part κ is the extinction coefficient. The Fresnel complex reflection r_{ij} and transmission coefficients t_{ij} at interface ij form the interface matrix I_{ij}

$$I_{ij} = \frac{1}{t_{ij}} \begin{bmatrix} 1 & r_{ij} \\ r_{ij} & 1 \end{bmatrix}.$$

The Fresnel complex reflection and transmission coefficients are defined by

$$r_{ij} = \frac{N_i - N_j}{N_i + N_j}, \quad t_{ij} = \frac{2N_i}{N_i + N_j}.$$

The layer matrix (phase matrix) describing the propagation through layer i is described by

$$L_i = \begin{bmatrix} e^{-i\xi_i d_i} & 0 \\ 0 & e^{\xi_i d_i} \end{bmatrix},$$

where

$$\xi_i = \frac{2\pi}{\lambda} q_i$$

and $\xi_i d_i$ is the layer phase thickness and q_i is the thickness of the layer. Finally, the transfer matrix S for the system is

$$S = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} = \left(\prod_{v=1}^{m} I_{(v-1)v} L_v \right) I_{m(m+1)}.$$

Therefore, the complex reflection and transmission coefficient can be expressed as

$$r = \frac{S_{21}}{S_{11}}, \quad t = \frac{1}{S_{11}}.$$

The reflectance spectra of samples with different Alq thickness were calculated first. For the samples without microcavity structure, no obvious interference peaks can be observed, as shown in Fig. 3(a). The reflectance spectra are very similar especially for the samples with thickness of 63, 92, and 95 nm, making the fitting extremely difficult and highly inaccurate. The weak interference is caused by the

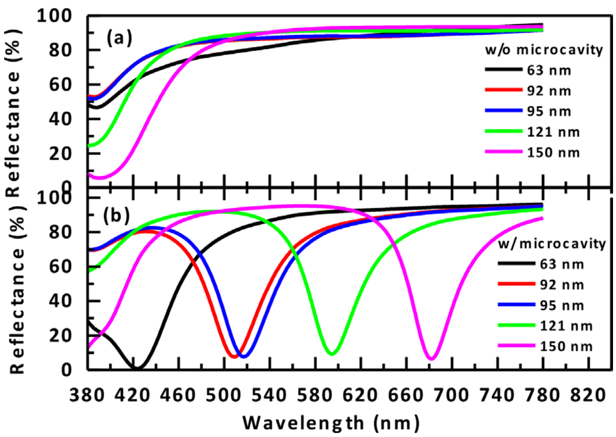

Figure 3 Calculated reflectance spectra of samples without microcavity (a) and with microcavity (b). With microcavity, the reflectance spectra exhibit sharp interference peaks. The position of the peaks is determined by the thickness of thin films.

low reflection of the top interface of the films. To enhance the interference, a thin Ag layer was capped on top of the film. As shown in Fig. 3(b), with the microcavity structure, the reflectance spectra exhibit distinctive and sharp peaks which are resulted from the destructive interference. The position of the destructive interference peaks, determined by $\lambda = 4Nd$, move to longer wavelength as the thickness increases. The position of the peaks is very sensitive to the thickness of the films. A small change of thickness can induce a noticeable shift of the interference peaks. For example, for samples with thickness of 92 and 95 nm, the thickness difference is only 3 nm, but the interference peaks with their position well separated by 10 nm, can be clearly distinguished, making the fitting easy and accurate.

The thickness of the top reflective mirror d_m can also be determined from the reflectance spectra. Figure 4 shows the calculated reflectance spectra of samples with different top mirror thickness. Obviously, the linewidth of the reflectance spectra becomes narrower when the thickness of top mirror increases. This is because the linewidth of the reflectance spectra is determined by [7]

$$\mathrm{FWHM} = \frac{\lambda^2}{2d} \times \frac{1-\sqrt{R_1R_2}}{\pi\sqrt[4]{R_1R_2}},$$

where R_1 and R_2 are the reflection of the bottom and the top mirror, respectively. Thicker top mirror leads to higher R_2 and thus induces stronger interference and results in narrower linewidth. It should be noted that, R_1 determined by the bottom mirror, is almost unchanged if the thickness of bottom mirror is larger than 60 nm. In our experiment, the bottom mirror is thick enough to guarantee a constant R_2, and therefore, its thickness does not affect the fitting result and it does not need to know its exact value for precisely fitting. Whereas the two unknown values d and d_m can be simultaneously and accurately extracted using our proposed microcavity structure. For example, by fitting the linewidth of the reflectance spectra, the thickness of the top mirror d_m can be precisely determined, whereas by fitting the position of the interference peaks, the thickness of organic films d can be accurately extracted. However, it should be noted that, the incident light would be completely reflected if the thickness of the top mirror is sufficiently large. For example, a 100 nm Ag film on glass can reflect ~95% of the incident light. If most of the incidence light is reflected back, the interference pattern is too weak to accurate fitting. In this regard, the optimal thickness of the top mirror should be in the range of 10–40 nm. As shown in Fig. 4, in this range, the sample can generate sharp interference pattern, and hence guarantee an accurate fitting result.

To further verify our assertion, samples with different thickness of organic thin films were fabricated. Figure 5 shows the measured reflectance spectra of samples without

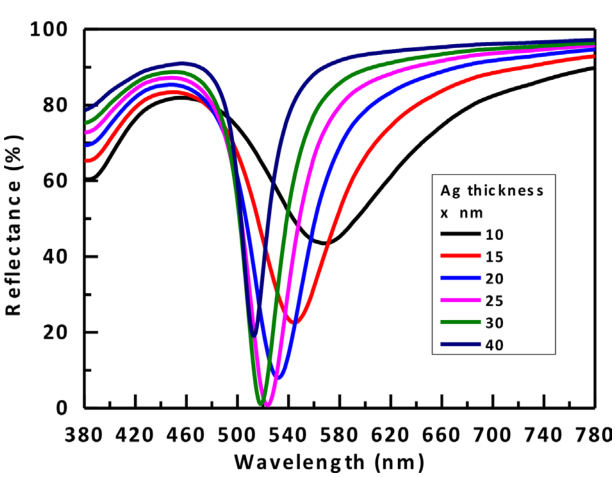

Figure 4 Calculated reflectance spectra of samples with different thickness of top mirror. The linewidth of the spectra is determined by the thickness of top mirror.

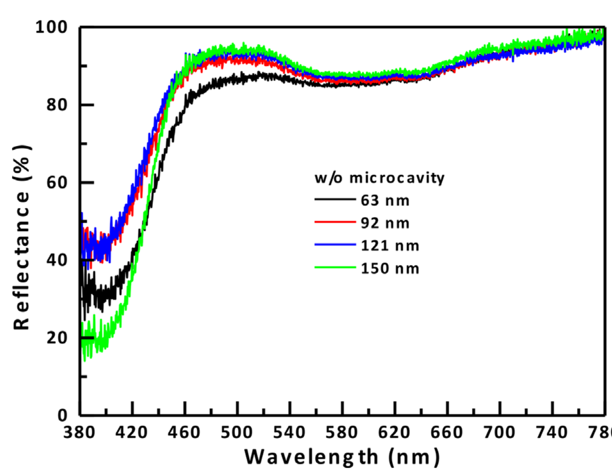

Figure 5 Measured reflectance spectra of samples without microcavity. The spectra are very similar; no distinguishable interference peaks can be observed, making precisely fitting impossible.

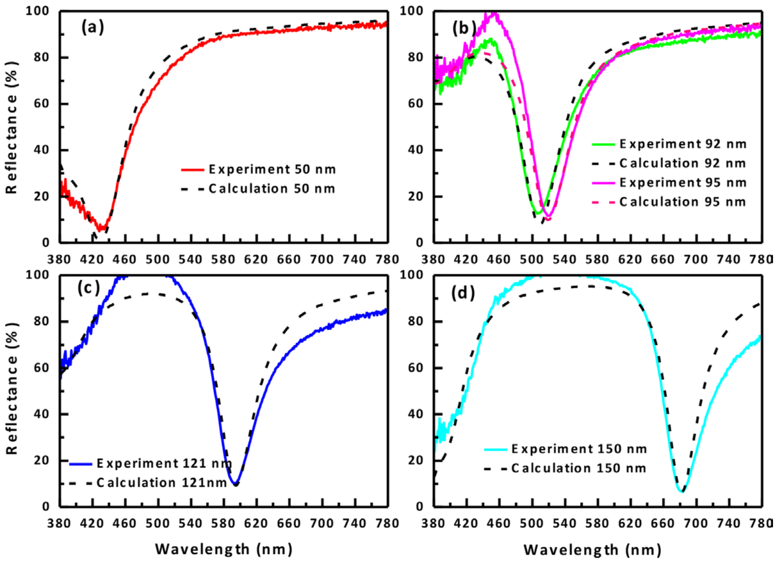

Figure 6 Measured reflectance spectra of samples with microcavity. All measured spectra can be accurately fitted. The thickness extracted from the fitting result agreed well with the measured value.

microcavity. Due to the weak interference, no distinguishable interference peaks can be observed. The reflectance spectra are quite similar, though their thickness is varied from 63 to 150 nm. Due to the high similarity, it is difficult to fit the spectra and extract the thickness from the fitting result. To differentiate the reflectance spectra, the interference should be enhanced, and it is achieved by further depositing a 20 nm Ag on top of the organic layer, which completes a microcavity structure. With the microcavity structure, the interference pattern can be clearly distinguished. As shown in Fig. 6, the interference pattern is determined by the thickness of the organic layer. The peaks red-shift as the thickness of organic layer increases. For example, the peak shifts from 430 to 510, 520, 590, and 680 nm if the thickness of the organic layer increases from 50 to 92, 95, 121, and 150 nm, respectively. As shown in Fig. 6(c) and (d), though there is a little deviation between the measured and the calculated reflectance spectra, the thickness can still be accurately extracted by fitting the interference peak. The peaks are very sensitive to the thickness of organic layer. A small change of thickness of organic layer can induce a noticeable variation of interference peaks. As a consequence, the reflectance spectra can be accurately fitted by the calculated data, and the thickness extracted from the fitting result is well agreed with the measured value. As shown in Fig. 6(b), even for a thickness difference of only 3 nm, the reflectance spectra can still be precisely fitted by the calculated data; therefore, the accuracy of the proposed method can be down to 3 nm.

3 Conclusions In summary, we have proposed a method for accurately measuring the thickness of the thin films. Using microcavity structure, the interference is greatly enhanced, and thus the reflectance spectra exhibit sharp and distinctive interference patterns, which is benefit for precisely fitting. By fitting the position of the interference peaks, the thickness of the organic layer can be determined, whereas by fitting the linewidth of the spectra, the thickness of the top mirror can be extracted. The developed method, only involving measurement of reflectance spectra using spectrometer, is simple, low cost, and particularly useful for accurately measuring the thickness of transparent and soft organic thin films.

Supporting Information

Additional supporting information may be found in the online version of this article at the publisher's web-site.

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