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Measurement on Interfacial Adhesion Property of Low-*k* Thin Film by the Surface Acoustic Waves Using the Cohesion Zone Model

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1. Introduction

The advances of ultralarge scale integrated circuits are being limited by the challenges in the development and reliable integration of new insulating materials with reduced dielectric constant *k* [1]. The reduction in the *k* value has been achieved by introducing a relatively high volume fraction of pores into the film, which has resulted in a challenge to integrate copper onto porous low-*k* materials due to their usually poor adhesion [2, 3]. An accurate and nondestructive method of measuring the low-*k* film adhesion is very significant and highly desired. In this study, the interfacial adhesion properties of low-*k* films are measured by the nondestructive laser-generated surface acoustic waves technique (LSAWs) with introducing the cohesion zone model (CZM). In the CZM, a critical fracture energy required to separate the film from the substrate is adopted to describe the relationship between the traction and the separation [4]. Obviously, it is very appropriate to introduce the cohesion zone model in the theoretical computation of SAW dispersion curves to evaluate the adhesion property of the film on the substrate. The interfacial adhesion property can be finally determined accurately by matching the experimental dispersion curve with the calculated theoretical dispersion curves. Our study shows the adhesion properties determined by CZM-SAW technique have the same trends with the results tested from the traditional nanoscratch technique.

2. Adhesion Property Determination by SAWs

Surface acoustic waves are dispersive on the layered structure. In the proposed method, the frequency *f* dependent SAW velocity (v_{SAW}) is determined by the Young's modulus (E), density (ρ), Poisson's ratio (σ), thickness (h) of the low-*k* film, the density (ρ), elastic constants (c_{11}, c_{12}, c_{44}) of the Si substrate [5], and the maximum normal traction (σ_{max}), normal characteristic length (δ_n) for the interface, as show in Eq.(1)

$$v_{SAW} = F(f, (E, \rho, \sigma, h)_{\text{film}}, (c_{\text{ij}}, \rho)_{\text{substate}}, (\sigma_{\max}, \delta_n)_{\text{interface}}) \quad (1)$$

The interfacial traction-separation law applied in this method is shown in Eq. (2)

$$T_n = \begin{cases} \dfrac{\Delta_n}{\delta_n}\sigma_{\max}, & T_n \le \sigma_{\max} \\ (1-D)\dfrac{\Delta_n}{\delta_n}\sigma_{\max}, & T_n > \sigma_{\max} \end{cases} \quad (2)$$

where T_n is interfacial normal stress, Δ_n is corresponding interfacial separation, and D is the damage variable, respectively. Fig. 1 represents the constitutive law which defines a constitutive relation between T_n and Δ_n. In this method, the constitutive relation of cohesion zone model is applied to describe the adhesion property of the low-*k* film. The interfacial stress is assumed to keep the film and substrate not separated from each other. Since the SAW technology is nondestructive, and the fluctuation energy is insufficient to the point of damaging the low-*k* film on the substrate, hence it is safe to use the above relation in the case of T_n is less than σ_{max}. Therefore, the traction-separation relation applied to the interface in the our theoretical calculation is given by Eq. (3)

$$T_n = \frac{\sigma_{\max}}{\delta_n}(\hat{u} - u) \quad (3)$$

where $\hat{u}$ and u are the particle displacements in the film and the substrate, respectively. The dispersive SAW properties can be calculated by the Matrix method [6].

In the experiment, a short pulse ultraviolet laser is applied to generate the SAWs by thermal-elastic effect, and the signal of SAWs can be transformed to electrical signal by a piezoelectric transducer. The experimental dispersion curves are obtained by FFT process on the detected signals.

3. Results and Discussions

Fig. 2 and Fig. 3 show the adhesion property detected by CZM-SAWs for dense Black Diamond and porous Black Diamond, respectively. The solid line is the experimental dispersion curve, and the dotted lines are dispersion curves obtained by theoretical calculation. Table 1 presents the parameters of samples. Young's modulus, thickness and density of the detected samples are measured by the nanoindentation test, X-ray reflectance and spectroscopic ellipsometry, respectively. As shown in Fig. 2 and Fig. 3, the precisely fitted values of σ_{max}/δ_n for dense and porous samples are 19.8 PPa/m and 6.5 PPa/m, respectively. Fig. 4 shows the traditional nanoscratch test result for the porous and dense Black Diamond film samples, respectively. The adhesion properties resulted from the SAWs measurement and the nanoscratch are listed in Table 2, which shows that the results of two measurement methods have the same trend.

Table 1 The parameters of the dense and porous Black Diamond.

Sample	Young's modulus	Thickness	Density
Dense Black Diamond	9.5 GPa	506.5 nm	1.38 g/cm^3
Porous Black Diamond	4.25 GPa	510.2 nm	1.1 g/cm^3

Table 2 Adhesion properties of SAWs and nanoscratch.

Sample	SAWs determined results	Nanoscratch critical load
Dense Black Diamond	19.8 PPa/m	8.269 mN
Porous Black Diamond	6.5 PPa/m	2.497 mN

3. Conclusions

The cohesion zone model is introduced in the laser-generated surface acoustic wave technique to measure the interfacial adhesion property between the film and the substrate. The interfacial adhesion properties determined for the dense and porous Black Diamonds by this promoted CZM-SAWs are 19.8 PPa/m and 6.5 PPa/m, respectively. Results show that the adhesion strength of the dense low-k film is stronger than that of the porous low-*k* film. These values have the same trend with the results from the traditional nanoscratch measurement. This study demonstrates that the proposed CZM-SAW technique has high reliability to be a nondestructive and accurate method for detecting the adhesion property of low-*k* films.

Acknowledgements

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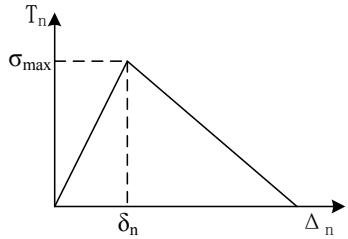

Fig. 1 Interfacial normal stress-normal separation law.

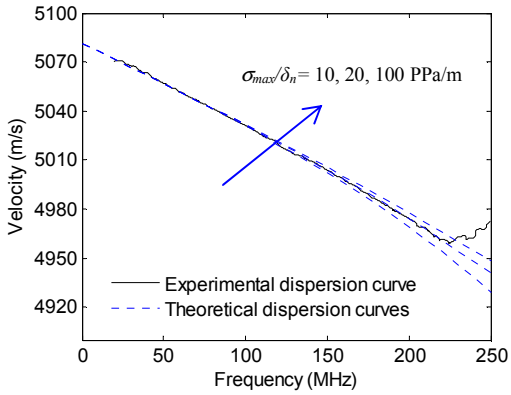

Fig. 2 Young's modulus determination of dense Black Diamond film by fitting experimental curves (solid line) with theoretical curves (dotted line).

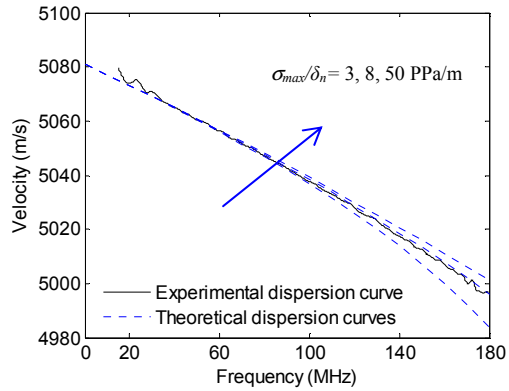

Fig. 3 Young's modulus determination of porous Black Diamond film by fitting experimental curves (solid line) with theoretical curves (dotted line).

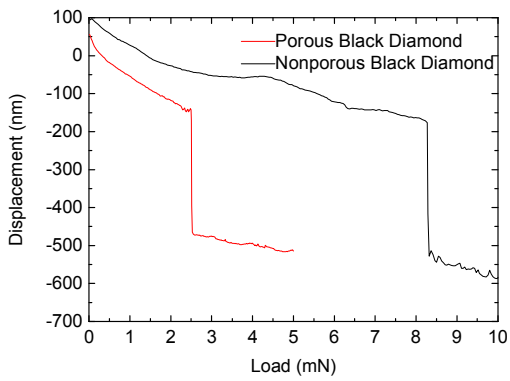

Fig. 4 Nanoscratch test results for the porous and the dense Black diamonds, respectively.