Influence of roughness on the detection of mechanical characteristics of low-k film by the surface acoustic waves*

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The surface acoustic wave (SAW) technique is a precise and nondestructive method to detect the mechanical characteristics of the thin low dielectric constant (low-k) film by matching the theoretical dispersion curve with the experimental dispersion curve. In this paper, the influence of sample roughness on the precision of SAW mechanical detection is investigated in detail. Random roughness values at the surface of low-k film and at the interface between this low-k film and the substrate are obtained by the Monte Carlo method. The dispersive characteristic of SAW on the layered structure with rough surface and rough interface is modeled by numerical simulation of finite element method. The Young's moduli of the Black Diamond^{TM} samples with different roughness values are determined by SAWs in the experiment. The results show that the influence of sample roughness is very small when the root-mean-square (RMS) of roughness is smaller than 50 nm and correlation length is smaller than 20 μm. This study indicates that the SAW technique is reliable and precise in the nondestructive mechanical detection for low-k films.

Keywords: low-k film, mechanical character detection, rough surface, rough interface, surface acoustic wave

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1. Introduction

Low dielectric constant (low-k) materials are essential for the advanced ultra-large scaled integrated (ULSI) interconnection. The integration of Cu and low-k materials meets the requirement for ULSI interconnection by reducing both resistivity and capacitance.[1] In order to obtain ultra low-k ($k < 2$) materials, nanopores should be induced into bulk materials. This process inevitably results in poor mechanical characteristics, which leads to serious reliability problems and restricts the chemical mechanical polishing (CMP) process of ULSI.[2–4] Hence, the good mechanical property of low-k film is essential to realize the application of low-k film in the advanced metallization system. Therefore, the accurate Young's modulus determination method for low-k film is highly desired. There have been a series of techniques to determine the mechanical properties of thin low-k film deposited on substrate.[5–7] The laser-generated surface acoustic wave (LSAW) method is a promising technique to detect the Young's modulus of thin low-k film quickly and nondestructively.[8–12] The phase velocity of SAW is dispersive while propagating on the layered structure. The parameters of low-k film, such as Young's modulus, density, and thickness, can be obtained by matching the experimental dispersion curves with the theoretical dispersion curves. The dispersion features of SAW propagating on the layered structure can be obtained by the Green's function and matrix method.[13,14] Generally, the film surface and interface between the film and the substrate are assumed to be ideally smooth in the theoretical model. The purpose of this paper is to investigate the influences of the surface roughness and the interface roughness on the reliability of SAW method. In the present study, the finite element method is used to obtain the theoretical dispersion features of SAWs propagating on the layered structure by considering the film roughness and the interface roughness. A random rough surface and an interface are established by the Monte Carlo method.[15,16] The random rough surface and interface are characterized by the parameters of root-mean-square (RMS) and correlation length. RMS is a measure of the deviation of out-of-plane roughness from the mean, and correlation length is a measure of the mean distance between peaks and valleys on a roughness profile.[17] By the finite element method, the eigen-frequencies of SAWs with different wavelengths are calculated. The velocities of SAWs are acquired by multiplying the wavelength with the eigen-frequency. Thus, the dispersion curves of SAWs propagating on rough model with various parameters of low-k film are obtained. The influence of roughness on the SAWs method can be evaluated by comparison with the dispersion curves from an ideal model (i.e., roughness-free model).

2. Random rough surface

The random rough surface and interface can be generated around the mean line by the Monte Carlo method. The surface and interface are generated at the upper and lower boundary by using a random function with two parameters, RMS δ and

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correlation length λ. The RMS is defined as the variance

$$\delta = \langle h^2 \rangle^{1/2}, \tag{1}$$

where $\langle\ \rangle$ means the average value, the parameter h is the sampling height of the surface, which accords with a Gaussian distribution expressed as[18,19]

$$f(h) = \exp\left[-h^2/2\delta^2\right]/\delta\,(2\pi)^{1/2}. \tag{2}$$

A correlation function is defined to describe the similarity between two points x and x–τ as[18,19]

$$R(\tau) = \langle h(x)\,h(x-\tau)\rangle/\delta^2. \tag{3}$$

A Gaussian correlation function is usually defined as[18,19]

$$R(\tau) = \delta^2 \exp\left(-\tau^2/\lambda^2\right), \tag{4}$$

where λ is the characteristic space length of correlation in statistics and describes the typical distance between two similar features (e.g. hills or valleys).[18,19] Figure 1 shows the random roughness established by the Monte Carlo method with different values of RMS δ and correlation length λ.

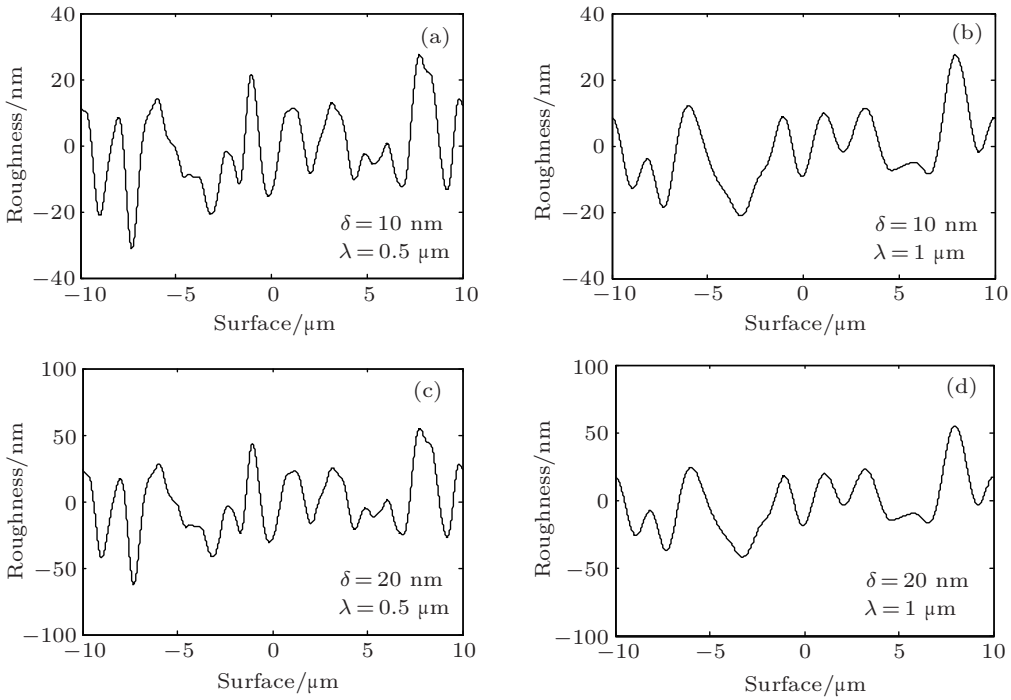


Fig. 1. Random roughness profiles with different values of RMS δ and correlation length λ for the cases of (a) $\delta = 10$ nm, $\lambda = 0.5$ μm; (b) $\delta = 10$ nm, $\lambda = 1$ μm; (c) $\delta = 20$ nm, $\lambda = 0.5$ μm; and (d) $\delta = 20$ nm, $\lambda = 1$ μm.

3. Finite element method (FEM) for dispersion curve of surface acoustic waves

Since it is difficult to establish an analytical computation model by the matrix method to obtain the theoretical dispersion curve of SAWs on low-k film with roughness, a numerical simulator based on the FEM is employed to study the SAW dispersive characteristics.

Generally, a line laser source is used in the SAW experiment to generate the SAWs, the displacement components of SAWs are in the sagittal plane. Hence, the simulation model is constructed in two dimensions to simplify the modeling. Figures 2(a) and 2(b) show the rough states at the surface of low-k film and interface between low-k film and substrate, respectively. In order to improve the computational speed, a periodic structure model of only single wavelength is employed in the simulation. The width of the model is set to be one wavelength of SAW. Since the penetration depth of SAW is approximately one wavelength, the thickness of the substrate is set to be two wavelengths in order to have enough thickness. At the top of the film, the free stress boundary condition is used while a fixed boundary condition is employed at the bottom of the substrate, where the SAW displacement can be neglected. The periodic boundary condition is applied to the right and left boundaries, where the displacement components (u, w) can be expressed as $u_{\text{left}} = u_{\text{right}}$, and $w_{\text{left}} = w_{\text{right}}$, respectively. Using the finite element method, the eigen-frequencies of SAWs with different wavelengths are calculated by modal analysis, and the velocities of SAWs are acquired by multiplying the wavelength with the corresponding eigen-frequencies ($v = \lambda \times f$). Thus, the theoretical dispersive curves of SAWs propagating on the rough model with various parameters of film on substrate are obtained.

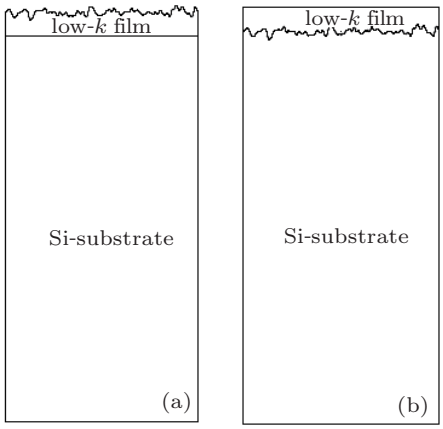


Fig. 2. Schematic diagrams of the models with roughness (a) on the surface of low-k film and (b) at the interface between low-k film and Si-substrate.

4. Results and discussion

In this study, the dispersion curves of SAWs propagating on the layered structure of low-k film on the Si substrate are simulated based on the roughness simulation models shown in Fig. 2. The relevant parameters of the simulation models are the same as those of the sample from Chartered Semiconductor Manufacturing Ltd. The density of Si is 2.329 g/cm^3. The low-k film is Black Diamond^{TM}, with a thickness of 500 nm, density of 1.38 g/cm^3, and Young's modulus of 9.5 GPa. Based on the advanced semiconductor process, the roughness of the surface could be limited in a nanoscale. Since the roughness of some low-k surface is greater after some treatments, such as direct CMP or certain reactive ion etching (RIE), the RMS δ is assumed to range from 1 nm to 50 nm and the values of correlation length λ are set to be 0.5, 1, and 2 μm, respectively, in the simulated model. The SAWs are arranged to propagate along Si [100] in the study.

Figure 3 shows the dispersion curves of SAWs for the model with different values of surface roughness. The RMS δ varies from 1 nm to 50 nm, the correlation length λ is 2 μm in Fig. 3(a); and the correlation length λ is set to be 0.5, 1, 2 μm, the RMS δ is 20 nm in Fig. 3(b). The blue (dashed) lines are dispersion curves with surface roughness, obtained by the finite element method. These dispersion curves show that the influences from both the RMS and the correlation length are quite small. The red (solid) lines are the dispersion curves of the ideal model when Young's moduli are 8.5, 9.5, and 10.5 GPa, respectively. Comparing the dispersion curve with surface roughness with the ideal one, the dispersion curves with surface roughness are approximately close to the ideal dispersion curve and lie within the range determined by the dispersion curves of the ideal model when Young's moduli are 8.5 GPa and 10.5 GPa. The effect of surface roughness on Young's modulus of film is less than 1 GPa. Hence, the effects of surface roughness with different values of RMS δ and correlation length λ on mechanical characteristic detection can to some extent be ignored.

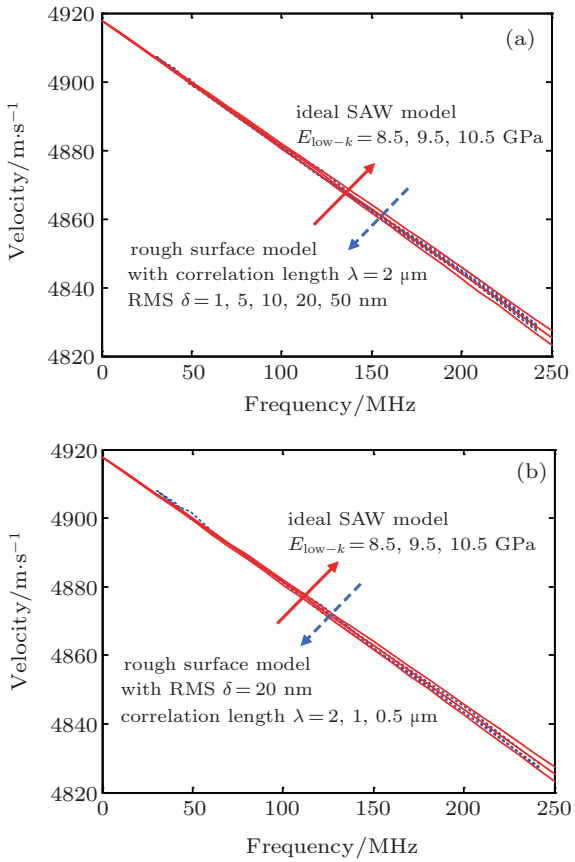


Fig. 3. (color online) Dispersion curves of SAWs depending on the Young's modulus of low-k film in the rough surface model with (a) different RMS values and (b) different correlation lengths.

Then, the effect of roughness at the interface between low-k film and substrate is investigated. Figure 4 shows the results simulated by finite element method. Figure 4(a) shows the effects of variation of RMS δ of roughness at the interface when the RMS δ varies from 1 nm to 50 nm, with correlation length λ fixed to be 2 μm. The effect of correlation length λ is shown in Fig. 4(b) when the values of correlation length λ are assumed to be 0.5, 1, 2 μm, with the RMS δ fixed to be 20 nm. The blue (dashed) lines are the dispersion curves with roughness at the interface, obtained by the finite element method. The red (solid) lines are the dispersion curves of the ideal model for different Young's moduli of low-k film. Figure 4 shows the dispersion curves with different roughness values at the interface between low-k film and substrate are close to the ideal dispersion curve. They also lie within the range determined by the dispersion curves of the ideal model with Young's moduli of 8.5 GPa and 10.5 GPa. Likewise, the effects of interface roughness with different RMS δ and correlation length λ on mechanical characteristic detection can also be ignored.

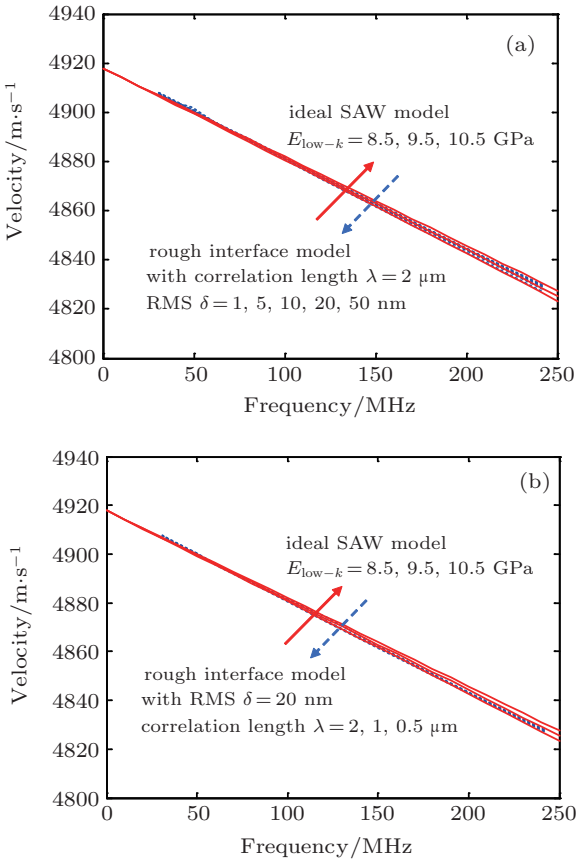


Fig. 4. (color online) Dispersion curves of SAWs depending on the Young's modulus of low-k film in the rough interface model with (a) different RMS values, and (b) different correlation lengths.

In the experiment, a short pulse ultraviolet laser is used to generate the SAWs by thermal-elastic effect. The SAW signal can be transformed to an electrical signal by a piezoelectric transducer. The experimental dispersion curves are obtained by fast Fourier transform (FFT) process on the detected signals. There are two Black Diamond$^{\text{TM}}$ samples measured in this experiment, one has a surface roughness of 1.2 nm, and the other has 59.1 nm. The surface roughness values of the detected samples are measured by using atomic force microscope (AFM). Figure 5 shows the dispersion curves of the samples, determined by SAWs. The black (short dashed) line and green (long dashed) line are the experimental dispersion curves with the surface roughness values of 1.2 nm and 59.1 nm, respectively. The red (solid) lines are the dispersion curves, obtained by theoretical calculation. As shown in Fig. 5, the experimental dispersion curves for the Black Diamond$^{\text{TM}}$ samples are close to the theoretical dispersion curves with Young's moduli of 8.5 GPa and 10.5 GPa, respectively. By using the matching algorithms, the fitted values of Young's modulus for the samples are calculated to be 9.6 GPa and 9.1 GPa, respectively. The measurement results evaluated by SAWs verify the simulated results based on the FEM, which shows that the effect of roughness on mechanical characteristic detection can be safely ignored.

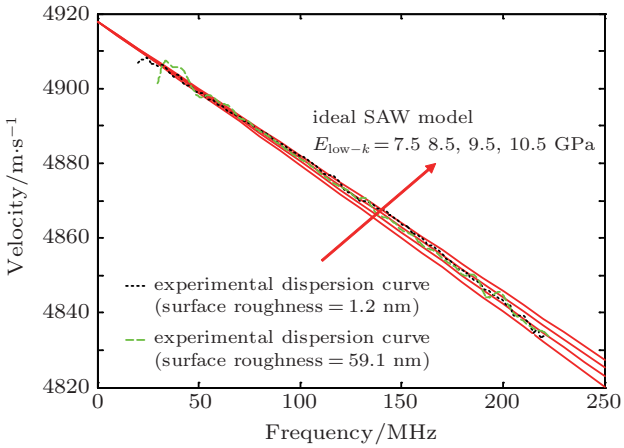


Fig. 5. (color online) SAW dispersion curves for the Black Diamond$^{\text{TM}}$ samples. The red (solid) lines are theoretical dispersion curves, and the black (short dashed) line and the green (long dashed) line are experimental dispersion curves with different roughness values.

5. Conclusions

The influence of random roughness at the surface of low-k film and at the interface between the low-k film and Si substrate on the detection of mechanical characteristics by SAWs is investigated by a finite element model. Random roughness established by the Monte Carlo method is used to represent the roughness of the samples. The RMS values of roughness are set to be in a range from 1 nm to 50 nm, and the correlation lengths are set to be 0.5, 1, 2 μm, respectively. The simulated results show that the random roughness values both at the surface of the low-k film and at the interface between this low-k film and substrate have a very small influence on the dispersion curve of SAW. The Young's moduli of the Black Diamond$^{\text{TM}}$ samples with different roughness values are determined by SAWs, and the measurement results verify the simulated results based on the FEM. According to this study, the influence of roughness could be safely ignored when a mechanical characteristic is detected by the SAW method for obtaining the theoretical dispersion curve of the low-k film. This research indicates that Green's function method and matrix method based on the ideal model could be safely used for the mechanical determination by SAW.

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