Numerical modeling of laser-induced picoseconds ultrasound in micro-nano thin films

Xu Baiqiang *[a)], Luo Ying [**], Xu Chenguang [*], Xu Guidong [*]

[*]*Faculty of Science, Jiangsu University, Zhenjiang 212013, China*

[**]*Faculty of Civil Engineering & Mechanics, Jiangsu University, Zhenjiang 212013, China*

Summary Owing to the advantages such as non-contact, high spatial and temporal resolution, etc., laser picosecond ultrasonic has been used in the detection of Micro-Nano-films. Based on the coupling of Two Temperature Model (TTM) and thermal elastic theory, a finite element numerical model of a short-pulse laser-induced ultrasound has been developed in multilayer thin films. The results show that the Two Temperature model is more reasonable in the study of laser picosecond ultrasonic than the classical Fourier heat transfer model.

Introduction

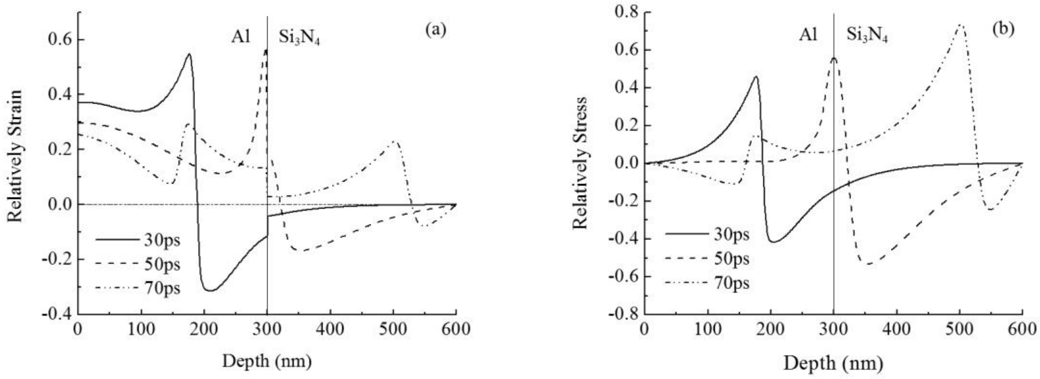
Micro-Nano-film is an important part of Micromechanical devices. The parameters of Micro-Nano-films are usually different from the mechanical parameters of corresponding bulk material, and the presence of residual stresses in the material will directly affect the device performance. Therefore, the research of the mechanical properties of Micro-Nano-film materials has its theoretical and practical significance. Owing to the advantages such as non-contact, high spatial and temporal resolution, etc., laser picosecond ultrasonic has been used in the detection of Micro-Nano-films [1]. By analyzing the propagation characteristics of laser ultrasonic, the mechanical parameters and the information of defects inside the material will be obtained [2]. Based on the coupling of Two Temperature Model (TTM) and thermal elastic theory, a finite element model of a short-pulse laser-induced ultrasound has been developed for numerical simulation of stress, strain and surface displacement response in Al/Si3N4 and Al/Si3N4/Si multilayer thin films.

Numerical model

Considering a short-pulse laser irradiation to the film surface, the model can be simplified to a one-dimensional model in the laser irradiation direction if the laser spot size is much larger than the thickness of the thin film. By coupling the Two Temperature equation with the thermoelastic equation, the solution of displacement fields can be obtained with the boundary conditions of stress-free taken into consideration. Furthermore, temporal and spatial resolution of the finite element algorithm is also critical to the convergence of the numerical results.

Simulation results and analysis

The curve of strain variation with depth in an Al/Si3N4 films along the z-axis direction is shown in Figure 1a. According to the location of peak, the propagation velocity of ultrasound in Al and Si3N4 film can be obtained respectively (about 6250 $m \cdot s^{-1}$ and 10100 $m \cdot s^{-1}$). Reflection and transmission occur while the peak of strain spread to the interface at about 50ps, then the strain the peak can be seen clearly in two layers at about 70 ps. The peak is significantly lower than the amplitude in 30 ps and 50 ps. The displacement response peaks are shown in Fig.2 as one or more reflected waves propagated to the Al surface. The stress and strain peaks show similar propagation characteristics, which can be seen from Fig.1b. In addition, the stress amplitude in Si3N4 is larger than in the Al film, which is due to the larger stiffness of Si3N4 than in Al.



（a）strain （b）stress

Fig.1 strain and stress at 30ps, 50ps and 70ps

[a)] Corresponding author. Email: bqxu@ujs.edu.cn.

The surface displacement of Al is shown in Fig. 2. The solid line and dotted line represent Al/Si3N4 structure and Al/Si3N4/Si, respectively. It can be seen that the amplitude of surface displacement response without substrate shows a larger decrease than in the Al film with Si substrate, which is caused by transmission of ultrasonic energy. Calculations show that the reflection coefficient of acoustic energy is 0.87 if the attenuation of ultrasound is ignored and only reflection and transmission of energy at the interface are considered. This indicates that most of the energy will be transmitted to the silicon substrate and only a small part of the energy reflected back to the Al surface through Al/Si3N4 interface and bottom surface of Si3N4, which will form response peaks. Therefore the larger the number of reflections is, the greater the attenuation of the response peaks will be.

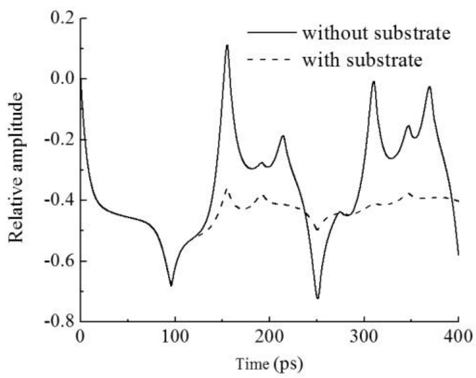


Fig 2 Surface displacement of Al/Si3N4 and Al/Si3N4/Si

CONCLUSIONS

The comparison of the computational results which was based on TTM theory and classical Fourier heat transfer theory respectively indicated that it was more suitable to use TTM theory in picoseconds ultrasonic investigation. Smaller amplitude and wider waveforms can be seen in the numerical results. The peaks emerging in displacement response spectrum on Al surface were induced by ultrasound reflection at the interfaces of films. The amplitude of the peaks attenuated rapidly when Si substrate was infinite, which indicated that a majority of ultrasonic energy has transmitted to the substrate.

References

[1] Stoner R J, Morath C J, Tas G, et al. Recent progress in picosecond ultrasonic process metrology[J]. AIP Conference Proceedings, 2001, 550(1): 468−478.

[2] Li T C, Pu N W, Lwo B J, et al. The effects of oxygen partial pressure on the acoustic velocity in zirconia films studied by picosecond ultrasonics. *Thin solid films*[J], 2006, 496(2): 208−213.

[3] Chen J, Beraun J, Grimes L, et al. Modeling of femtosecond laser-induced non-equilibrium deformation in metal films. *International journal of solids and structures*[J], 2002, 39(12): 3199−3216.