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Thermo-mechanical solution of film/substrate systems under local thermal load and application to laser lift-off of GaN/sapphire structures

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ABSTRACT

Film/substrate structures may undergo a localized thermal load, which can induce stresses, deformation and defects. In this paper, we present the solutions of temperature and stresses in a film/substrate structure under a local thermal load on the film surface. Then, the generalized Stoney formula, which connects the curvature of deformation and the stress field is obtained. The present solution takes into account the non-uniformity of the temperature field both in the width and thickness directions of the film. The thermo-mechanical solution is applied to the analysis of the temperature distribution, stresses, and damage of a GaN/sapphire system during the laser lift-off (LLO) process. It is shown that the laser with the Gaussian distribution of energy density causes much smaller tensile stresses at the edge of the heated area in the film than the laser with the uniform distribution of energy density, and thus can avoid damage to the GaN films separated from the substrate.

1. Introduction

Film/substrate structures are widely used in microelectronic and optoelectronic devices for decades and these structures usually undergo a local thermal load in applications (e.g., Bowden et al., 1998; Freund and Suresh, 2003; Chui et al., 1998; Gotsmann et al., 2010). The mismatch of the coefficients of thermal expansion (CTE) between the film and the substrate causes deformation and stresses in the structure, and the stresses may in turn induce defects in the film, and influence the properties of the device. For example, the thermal atomic force microscopy (AFM) or scanning thermal microscopy (SThM) probe is used to heat poly ethylene terephthalate (PET) films to induce crystallization of the material (Zhou et al., 2008; Duvigneau et al., 2010), and the SThM is also used in nanoscale lithography on molecular resist films to fabricate various microstructures (Mamin, 1996; King et al., 2006; Szoszkiewicz et al., 2007; Lee et al., 2008; Pires et al., 2010). A similar situation arises in the laser lift-off technique (LLO; Elgawadi and Krasinski, 2008; Sun et al., 2008) for separating GaN films from substrates. The working principle of the LLO technique is to use a laser beam to heat the interface between the film and the substrate. The GaN near the interface heated by the laser decomposes into metal Ga and nitrogen gas, so the film is separated from the substrate under a proper temperature. During the LLO process, the laser heating results in a non-uniform temperature distribution in the film both in the width and thickness directions. This non-uniform temperature distribution results in stresses, bending, and even damage in the film (Jain et al., 1996; Kaiser et al., 1998; Zheng et al., 2007; Jang et al., 2010). Therefore, in these techniques, the details of the temperature distribution and stresses in the target films on the substrates are essential to an accurate control of the microstructures of the products.

The deformation of a film/substrate structure due to a thermal loading and/or surface stress has been paid much attention (e.g., Stoney, 1909; Freund and Suresh, 2003; Zhang and Dunn, 2004; Huang and Rosakis, 2005; Weissmüller and Duan, 2008; Yi and Duan, 2009). The Stoney formula gives the relation between the film stress and the curvature (Stoney, 1909). However, the Stoney formula is only valid under six assumptions, the details of these assumptions can be found in the work of Huang and Rosakis (2005). With the developments of nanotechnology and biotechnology, the Stoney formula is widely used and generalized to different situations. Freund (2000) obtained the relation between the mismatch strain and the curvature in a film/substrate system in the nonlinear deformation range; Huang and Rosakis (2005, 2007) relaxed the sixth assumption, namely, all of the stress and curvature components are constant over the whole surface of the film, and derived the generalized Stoney formula for film/substrate structures under a temperature distribution, which is non-uniform in

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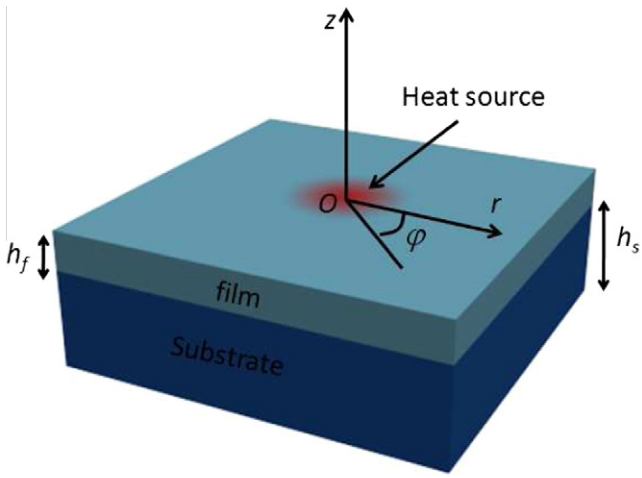

Fig. 1. Schematic diagram of a film/substrate structure.

the width direction and uniform in the height direction of the structure. Feng et al. (2006, 2008) applied the theory of Huang and Rosakis (2005) to a thin film/substrate system with different radii and the multi-layer film/substrate structures, and obtained the stress distribution under a non-uniform temperature distribution in the direction of the span (Feng et al., 2008).

Damage in film/substrate structures under various mechanical loading conditions has been extensively and intensively explored. Hutchinson and Suo (1992) summarized several common damage patterns in film/substrate structures, and gave the critical conditions for the defect emerging. Zhu et al. (2005) simulated the crack formation from pegs in thermal barrier systems, and estimated the critical conditions for the initiation and propagation of the cracks. Pramanik and Zhang (2011) investigated the residual stress and fracture in a silicon-on-sapphire system, and found that the fracture can be minimized by controlling the thickness of the buffer layer. Besides damage analysis of film/substrate structures in the field of solid mechanics, there exist some studies of the mechanical problems of LLO (Kozawa et al., 1995; Tavernier and Clarke, 2001; Elgawadi and Krasinski, 2008). In these analyses, the temperature in the film induced by the laser heating is assumed to be uniform, but the temperature is found to be actually non-uniform both in the width and the height directions in experiments (Sun et al., 2008; Sun, 2009). This non-uniformity of the temperature in the film during the LLO process is due to two factors. The first is that the energy density of the laser may be non-uniform; for example, the commonly used laser energy density satisfies the Gaussian distribution. The second is that the heat transfer during the LLO process can induce the non-uniformity of the temperature. The experiments of Sun (2009) show that cracks usually occur at the edge of the laser irradiated area, while almost no crack appears in the center of the irradiated area; and the GaN films separated by the laser with the Gaussian energy density have fewer defects than those by the laser with uniform energy density.

At present, to the authors' knowledge, there is no thermo-mechanical solution to the temperature and stress distributions in film/substrate structures under a local thermal load on the film surface. In particular, a systematic analysis of the temperature distribution, stress fields, and damage of the GaN/sapphire structures in the LLO technique is lacking. In this paper, we present the solutions of temperature and stress distributions in a film/substrate structure under a local thermal load on the film surface. Then, the connection between the film stress and the curvature of deformation of the structure under the non-uniform temperature distribution is established. Finally, we apply the solutions to the LLO process of a GaN/sapphire structure, and analyze the stress field and damage mechanism of the separated GaN films.

2. Temperature distribution due to local thermal load

2.1. Temperature distribution in film/substrate structure

The schematic diagram of a film/substrate structure subjected to a local thermal load on the film surface is shown in Fig. 1. The thicknesses of the film and the substrate are h_f and h_s, respectively. The cylindrical coordinate (r, φ, z) is adopted, as shown in Fig. 1.

In the techniques of heat induced micro-cantilever sensors, the LLO of GaN films, and the thermal AFM probe heating, both the operation time and the conduction time of heat in the films are usually very short; therefore, the analysis is carried out under two assumptions: first, the interface between the film and substrate is adiabatic due to the large thermal resistance at the interface; second, the thermal interchange between the film surface and the environment is neglected. If the initial time, from which the film starts to be heated, is $t = 0$, the temperature $T(\mathbf{r})$ at a position $\mathbf{r}$ in the film satisfies (Bechtel, 1974),

$$\frac{\partial T}{\partial t} = \frac{1}{\rho C}\left[\frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right) + \frac{1}{r^2}\frac{\partial}{\partial \varphi}\left(k\frac{\partial T}{\partial \varphi}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)\right] \tag{1}$$

where ρ, C and k are the density, thermal capacity and thermal conductivity of the film, respectively.

As shown in Fig. 1, the film is heated on the surface ($z = 0$). For the interface between the film and substrate, when the application time of heat source on the film is very short and the film is thick, the heat cannot reach the interface. Moreover, for many kinds of film/substrate structures, the heat resistance at the interface is large. Therefore, the interface is assumed to be adiabatic (Wong, 1999). The boundary condition in Fig. 1 can be written as,

$$\left.\frac{\partial T}{\partial z}\right|_{z=-h_f} = 0, \quad k\left.\frac{\partial T}{\partial z}\right|_{z=0} = I(t, r, \varphi) \tag{2}$$

where $I(t, r, \varphi)$ is the energy density of the local thermal load.

By using the Green function method, we can get the solution to Eqs. (1) and (2), i.e.,

$$T = \frac{1}{\rho C}\int_0^t G_z \iint_{\Omega} I(t', r', \varphi')G(r, \varphi, t; r', \varphi', t')r'dr'd\varphi'dt' \tag{3}$$

where the Green functions G and G_z are given by (Bechtel, 1974),

$$G(r, \varphi, t; r', \varphi', t') = \frac{1}{4K\pi(t-t')} \times \exp\left(-\frac{r^2 + r'^2 + 2rr'\cos(\varphi - \varphi')}{4K(t-t')}\right) \tag{4}$$

$$G_z(z; t') = \frac{2}{[4K\pi(t-t')]^{1/2}}\sum_{n=-\infty}^{\infty}\exp\left(-\frac{(z + 2nh_f)^2}{4K(t-t')}\right) \tag{5}$$

where $K = k/(\rho C)$, Ω denotes the heated area. t', r' and φ' are variables. From Eq. (3), we can see that at any given time and position, the temperature distribution can be determined by the energy density and the application area of the local thermal load. Next, we will discuss two kinds of energy density.

2.1.1. Uniform energy density

If the local thermal load is uniformly distributed in a circular area with a radius of a (i.e., $I(t, r, \varphi)$ is a constant I_0), while the energy density is zero outside the circle, then the temperature distribution in the film is axially symmetric, and Eq. (3) becomes