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Residual stresses in silicon-on-sapphire thin film systems

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ABSTRACT

This paper uses the finite element method to analyse the generation and evolution of residual stress in silicon-on-sapphire thin film systems during cooling. The effects of material properties, thin film structures and processing conditions, on the stress distribution were explored in detail. It was found that under certain conditions, significant stress concentration and discontinuity can take place to initiate crack and/or delamination in the systems. However, these can be minimised by controlling the buffer layer thickness.

1. Introduction

Multi-layered thin film systems have been used in a broad range of fields such as in optical, electronic, mechanical and protective applications (McCann et al., 2001; Mylvaganam and Zhang, 2003; Pramanik et al., 2008a; Richmond and Knudson, 1982). The hetero-epitaxial process is used to generate multi-layered thin films of a semiconductor material, such as silicon, on insulated sapphire substrates for electronic circuits. The main advantages of the electronic circuits thus fabricated are that the highly insulating sapphire substrate of low parasitic capacitance can provide a higher speed, lower power consumption, greater linearity and better insulation (Imthurn, 2007). However, there are some problems associated with the fabrication of such systems, e.g., the high density of crystalline defects and the complex residual stresses. The mismatch of the lattice parameters and of the thermal expansion properties between thin film layers and substrate materials are the main causes of cross-layer defect development and residual stress generation (Nakamura et al., 2004; Yamamoto et al., 1979). Several methods have been proposed to minimise the residual stresses caused by lattice mismatch (Lau et al., 1979), such as ion implantation and annealing (Hull, 1999; Roulet et al., 1979; Vodenitcharova et al., 2007) of which the former is to introduce further disorder in the crystalline as-deposited structure and the latter is to regrow the crystalline layers.

Residual stresses in a thin film system are often detrimental to its performance. If sufficiently large, they can lead to buckling, cracking, void formation and film debonding (Freund and Suresh, 2003; Mei et al., 2007; Mylvaganam and Zhang, 2003). Therefore, a complete understanding of the residual stress generation in relation to fabrication processes is essential. Previous experimental and analytical studies (People and Bean, 1985; Tsao et al., 1987) have provided insight into the relationship between energies and misfit strain and dislocations. The stress generation mechanism in silicon-on-sapphire (SOS) thin film systems without buffer layers has also been partially investigated. Mavi et al. (1991) used the Raman spectroscopy to measure and compare the localised stresses of annealed, as-deposited and phosphorous ions implanted SOS thin films. To calculate stresses in thin film systems, the Stoney formula (Stoney, 1909) has been commonly used (Brown et al., 2007; Ha et al., 2006; Ngo et al., 2007; Shen et al., 1996). Feng et al. (2008) and Ngo et al. (2008) extended this formula to calculate the stresses in multi-layered thin films deposited on a substrate subjected to non-uniform misfit strains, which provides a way to determine experimentally the stresses in such systems. Although the analytical and experimental methods, including the wafer curvature (Flinn, 2008; Shen et al., 1996) and X-ray (Flinn and Waychunas, 1988; Flinn and Chiang, 1990) methods, are useful, they have some major disadvantages: (i) they can give only the average and local stresses in a volume; (ii) they cannot provide the stress variation, distribution and directions in a thin film system during fabrication; and (iii) they cannot reveal stress discontinuity across individual layers.

The finite element (FE) method is an efficient technique for studying complex systems (Pramanik et al., 2007, 2008), including the study of residual stress analysis of a multi-layered thin film system. Subramaniam and Ramakrishnan (2003) used a two-dimensional FE calculation to understand the threshold thickness

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