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Determination of Temperature-Dependent Stress in SiC MOSFETs by Raman Spectroscopy

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Abstract

A procedure to determine the temperature-dependent stress in silicon carbide (SiC) power devices was developed using Raman spectroscopy. By applying this method to SiC metal-oxide-semiconductor field-effect transistors (MOSFETs) with discrete packages, we observed an upward shift of the folded transverse optic (FTO) mode with E_2 symmetry near the interface between the SiC chip and solder. The upward shift, which corresponds to the compressive in-plane stress, increased as temperature decreased. The main cause of the compressive stress was explained by the difference of coefficients of thermal expansion (CTE) between SiC and metals.

1. Introduction

Silicon carbide (SiC) is one of the wide-bandgap semiconductors and has many advantages suitable for power device application [1–3]. SiC power devices can be used at a wide range of operating temperature. Residual stresses at extreme environments may cause unintended effects by producing defects, cracks, or delamination. Low stress die-attach materials have intensively studied to improve reliability of the SiC power devices. However, experimental stress measurements for power devices are not straightforward because power devices consist of a wide variety of materials and have complex structures.

Raman spectroscopy is one of the most powerful techniques to measure local residual stress in semiconductor devices [4–7]. However, most studies have been conducted at room temperature because temperature change also shifts the Raman lines. Precise measurements of the peak shift and temperature control of the sample are needed to determine the temperature-dependent stress. In this work, we investigated fundamental behavior of the Raman lines in 4H-SiC and determined the temperature-dependent stress in SiC metal-oxide-semiconductor field-effect transistors (MOSFETs) based on the basic experiments.

2. Experiment

The SiC devices used in this study were commercially available 1200 V SiC MOSFETs with TO-247 discrete package. We mechanically cut the package and polished the cross section. A 457.9 nm line of an argon ion laser was used as an exciting light. We used a Jobin Yvon U1000 double monochromator and a charge coupled device (CCD) detector. A high-purity semi-insulating 4H-SiC wafer was used as a stress-free reference. A Linkam THMS600 temperature-controlled heating and cooling stage was used for the temperature-dependent measurements. We performed Raman measurements at 233, 296, and 413 K. The temperature of the sample was controlled within ± 0.5 K.

3. Results and Discussion

Figure 1 shows the Raman spectra of 4H-SiC crystal at various temperatures taken at a backscattering geometry from the (11-20) face. In this geometry, the folded transverse optic (FTO) modes with E_2, A_1, and E_1 symmetries are observable [8]. These modes shift toward lower frequency with increasing temperature. The temperature dependence of the peak frequency of the E_2 mode is shown in Fig. 2. According to theoretical calculations derived by Balkanski *et al.*, the frequency shift is represented by the following equation [9]:

$$\Delta(T) = C\left[1 + 2n(T, \omega_0 / 2)\right] + D\left[1 + 3n(T, \omega_0 / 3) + 3n^2(T, \omega_0 / 3)\right]. \quad (1)$$

The values C and D are the anharmonic constants for three- and four-phonon processes, respectively. The function $n(T, \omega)$ is the Bose-Einstein distribution function written as

$$n(T, \omega) = 1/\left[\exp(\hbar\omega / k_B T) - 1\right]. \quad (2)$$

The solid curve in Fig. 2 is a theoretical fit using eq. (1). The solid curve reproduces the experimental results very well. We can derive the shift due to the stress at certain temperature by subtracting the shift caused by temperature variation using eq. (1).

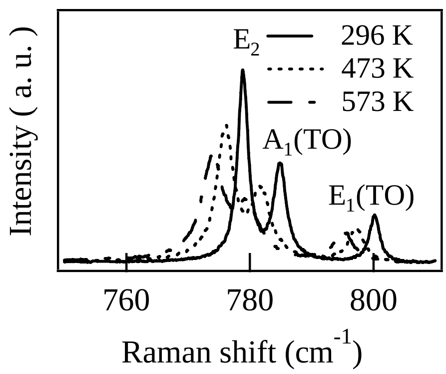

Fig. 1 Raman spectra of 4H-SiC crystal at various temperatures.

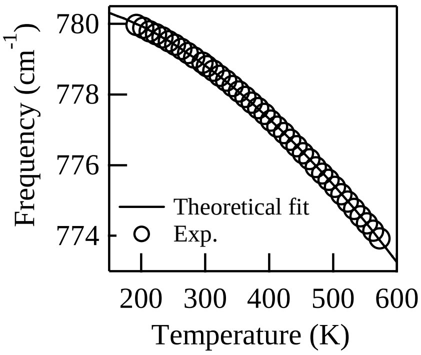

Fig. 2 Temperature dependence of the peak frequency of E_2 mode.

An optical micrograph and measurement points are shown in Fig. 3 (a). Points B and C are located near the interface between the chip and solder. The solder layer in this device consists of Sn, Ag, Cu, Sb elements from the compositional analysis. Figure 3 (b) shows the temperature dependence of the frequency shift of E_2 mode. Upward shifts are observed at points B and C, while a slight downward shift is observed at point A. In Fig. 3 (b), the frequency shift caused by temperature variation is fully compensated using eq. (1). The upward shifts increase as temperature decrease at points B and C, whereas no significant change is observed at point A. The atomic displacement of the E_2 mode is perpendicular to the c-axis and the E_2 mode is sensitive to the in-plane stress. Therefore, the observed upward shift suggests that the SiC chip near the interface is subjected to the compressive in-plane stress at low temperature. The A_1(TO) mode, whose atomic displacement is parallel to the c-axis, shows small shift as compared to the E_2 mode in our preliminary experiments. These results suggest that the stress component parallel to the c-axis is small as compared to the in-plane component in this SiC device. However, further detailed studies are needed to discuss the stress components quantitatively.

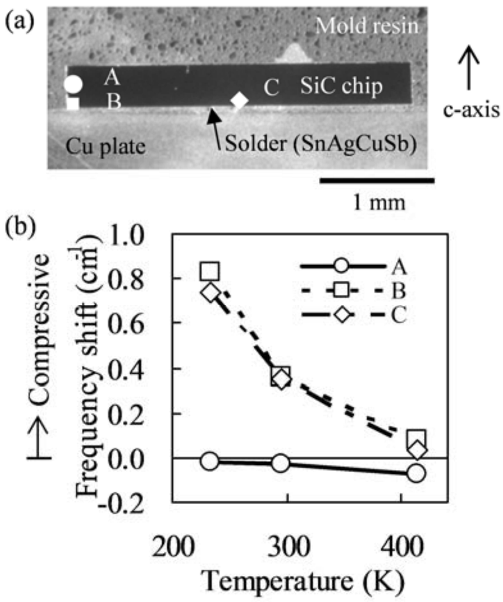

Fig. 3 (a) Optical micrograph of the sample and (b) frequency shift of E_2 mode at points A, B, and C. The frequency shift caused by temperature variation is fully compensated in these data.

The cause of the compressive in-plane stress at low temperature can be explained by the difference in the coefficient of thermal expansion (CTE) between metals (solder and Cu) and SiC. The CTEs of the solder (SnAgCuSb), Cu, and SiC are about 2–3 × 10^{-5}, 1.7 × 10^{-5}, and 4 × 10^{-6} K^{-1}, respectively [10–12]. The reflow temperature of the solder is about 500–520 K and the metals shrink more than the SiC chip below the reflow temperature of the solder. Therefore, the compressive in-plane stress in the SiC chip becomes large as temperature decreases.

4. Conclusions

A procedure to determine the temperature-dependent stress in SiC power devices was developed using Raman spectroscopy. The shift of the E_2 mode due to the stress at certain temperature was derived by subtracting the shift caused by temperature variation using Balkanski model. By applying this method to the SiC MOSFET, a compressive in-plane stress near the interface between the SiC chip and solder was observed. The observed compressive stress increased as temperature decreased. The main cause of the compressive in-plane stress was explained by the difference of CTEs between SiC and metals.

The temperature-dependent Raman measurement is effective for the determination of the residual thermal stress in SiC power devices and applicable for the investigation of low stress die-attach materials and the optimization of packaging of SiC power devices.

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