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The correlation of the results of capacitance mapping and of sheet resistance mapping in semi-insulating 6H–SiC

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ABSTRACT

A combination of complex surface capacitance mapping and sheet resistance mapping is applied to establish the origin of resistance variations on semi-insulating (SI) 6H–SiC substrates. The direct correlation between the capacitance quadrature and the sheet resistance is found in vanadium-doped SI samples. Regions with low capacitance quadrature show high sheet resistance. This indicates, associated with the nonhomogeneity of sheet resistance on the substrate, that the quality of crystallization is not good enough, which also leads to resistivity nonhomogeneity when comparing with different types of deep defects. According to the capacitance mapping, the region with bad crystallization quality has a high radio absorption coefficient. Another correlation is established between the capacitance in-phase and sheet resistance for the vanadium-doped sample. In this sample, the capacitance in-phase map shows not only the surface topography, but also the same distribution trend as the sheet resistance, namely, regions of high capacitance in-phase reveal high sheet resistance.

1. Introduction

Silicon carbide (SiC) is a rapidly developing semiconductor material for power devices owing to its superior physical and chemical properties such as good mechanical properties and excellent corrosion and oxidation resistance [1–5]. Especially, semi-insulating (SI) SiC substrates are critical for the development of GaN-based radio-frequency devices and SiC-based high power microwave transistors [6,7]. Compensation with vanadium-related deep levels has been one of the approaches used for achieving SI properties [7,8]. In addition, vanadium free (nominally undoped) SiC crystals with Fermi level pinned to deep-level native point defects have been extensively investigated. And various native defects as well as V-related deep levels are reported to be responsible for the SI behavior [6]. In this case, the crystallization quality of crystal also contributes to the resistivity nonhomogeneity in the SI wafer during the bulk growth process.

Several characterization techniques can be used for investigating properties of SI silicon carbide substrates, including resistivity and topography. A contactless resistivity mapping (COREMA) is used to evaluate SI properties of SiC and the uniformity of the resistivity distribution across the wafer [9]. Scanning electron microscope (SEM) is usually applied to observe the material surface topography. However, for the high resistivity case, the surface of the sample should be deposited a layer of conductivity film before SEM observation. This is not suitable for on-line test. In this work, non-contact resistance mapping, which concerned a surface-sensitive capacitive probing technique capable of contactless measurement of sheet resistance [10], is used to evaluate SI properties of SiC and the uniformity of the resistivity distribution across the wafer. And complex surface capacitance mapping is also applied to a V-doped SiC substrate to show a surface topography. This mapping technique is convenient and can be carried out with the resistance testing at the same time.

2. Experimental

Semi-insulating 6H–SiC substrates have been grown by using physical vapor transport (PVT) method in our group. A resistance map was obtained by using a non-contact resistance measurement system (provided by Sensa Wave Technology Inc., Burnaby, BC, Canada). This system is based on the Sommer–Tanner method for electrodeless electrical characterization, previously used for measurements on two-dimensional electron systems with a small scanning probe capable of accurately measuring local lateral transport in thin films and surfaces, providing a practical method for electrodeless in-line measurements on low conductivity semiconducting and semi-insulating thin films, compound semiconductors and similar materials [10]. The probe interface was a combination of an automated digital AC bridge and a digital dual phase locking amplifier with a fixed input gain of 1000 [10]. The capacitance resolution achieved with this interface was approximately 10 aF, corresponding to a balance resolution on the order of 1:100,000 [10]. This high sensitivity made it possible to detect very small variations in electrical impedance of the sample surface. The probe had an intrinsic capacitance of 144 fF and showed negligible resistive response in the frequency range considered here (80 Hz–10 kHz) [10]. Measurements were done by placing the probe in close proximity to the sample surface with a gap of approximately 300 μm, and recording the changes in capacitance with frequency. The upper detection limit for the technique is up to be 10^{12} Ω cm or more.

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Since two-inch sample was fragmented into several pieces, the main part had some parts of the edge missing. The complex surface capacitance mapping and resistance mapping are applied to this imperfect sample.

3. Results and discussion

As we know, the dielectric constant is a characteristic quantity of a given dielectric substance, sometimes called the relative permittivity [11]. In general, the dielectric constant is a complex constant, with the real part giving reflective surface properties (Fresnel reflection coefficients), and the imaginary part giving the radio absorption coefficient. There were several result sheets for the measured wafer, which included capacitance out-of-phase and in-phase except for measured sheet resistance, being the representations of the directly measured complex surface capacitance. The capacitance out-of-phase and in-phase represent imaginary and real parts of the dielectric constant, respectively. These results can reveal some wafer properties, such as surface topography. The sheet resistance mapping and capacitance quadrature (out-of-phase) mapping results are shown in Fig. 1.

Comparison between the capacitance quadrature map (Fig. 1a) and the sheet resistance map (Fig. 1b) shows a contrary corresponding correlation between the capacitance quadrature distribution and the resistance distribution. Namely, the regions with low capacitance quadrature correspond to high sheet resistance. From the above explanation, we know that the radio absorption coefficient of the SI substrate surface can be given by the capacitance quadrature. The data points on the surface of this imperfect wafer were up to 351. The range of capacitance variations across the main wafer area is from around −0.3855 to 3.2074 fF. Mean capacitance quadrature is 1.7187 fF with a relative standard deviation of 62.67%, which indicates that crystallization quality is not good enough, associated with the resistance nonhomogeneity of the substrate. The bright regions of the sheet resistance map represent the missing parts results, which are much higher than that of the other parts. So the deviation across the whole wafer must be lower than 62.67%. For the vanadium-doped substrates, the contribution of different types of deep defects (including native point defects as well as vanadium) was reported [6]. But from the above analysis, we can draw a conclusion that the resistance nonhomogeneity on the V-doped SI substrate is related with not only different types of deep defects, but also the crystallization quality.

The capacitance in-phase map was shown in Fig. 2. The bright regions with high sheet resistance were explained in the foregoing text. The range of capacitance variations across the main wafer area is around 0.2677–5.7869 fF. A relative standard deviation across the wafer is 46.73%. Comparison with sheet resistance map showed that there existed a corresponding correlation between the capacitance in-phase and sheet resistance. Regions of high capacitance in-phase with high sheet resistance can be observed in Figs. 2 and 3. And the capacitance in-phase map shows that there are some crystal grains in the right parts of the wafer, which lead to a resistance nonhomogeneity. If the crystal quality is high, no grains will be observed on the wafer surface in this method. In Fig. 3, the capacitance variations across the main wafer ranging from around 3.605 to 9.826 fF can be observed. The relative standard deviation across the wafer

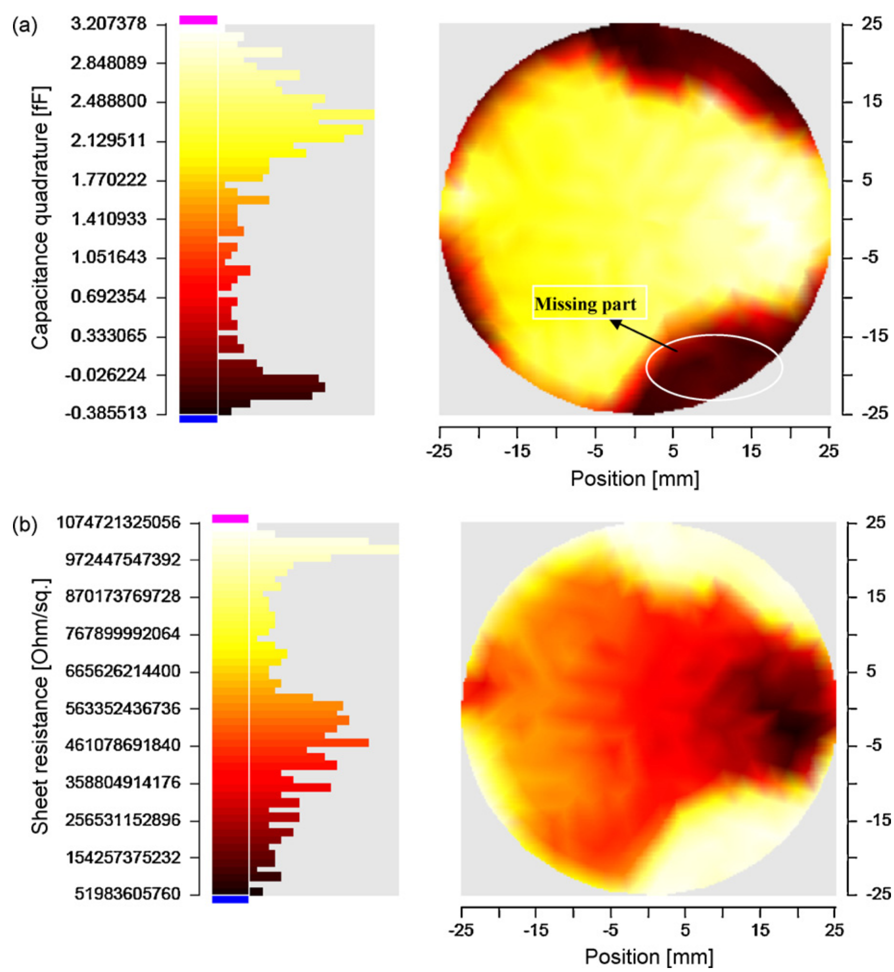

Fig. 1. Comparison of the (a) capacitance quadrature map and (b) sheet resistance map of vanadium-doped 6H–SiC substrate. A good correlation between the two maps can be observed.

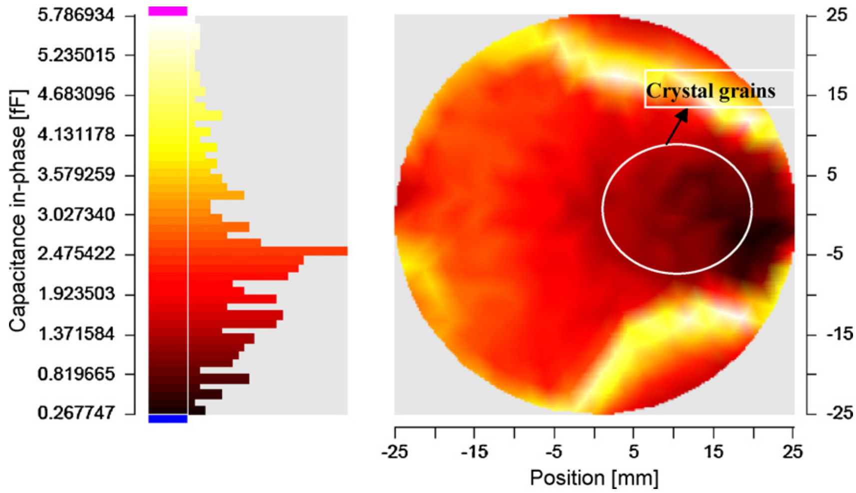

Fig. 2. Capacitance in-phase map of vanadium-doped 6H–SiC substrate with bad crystallization.

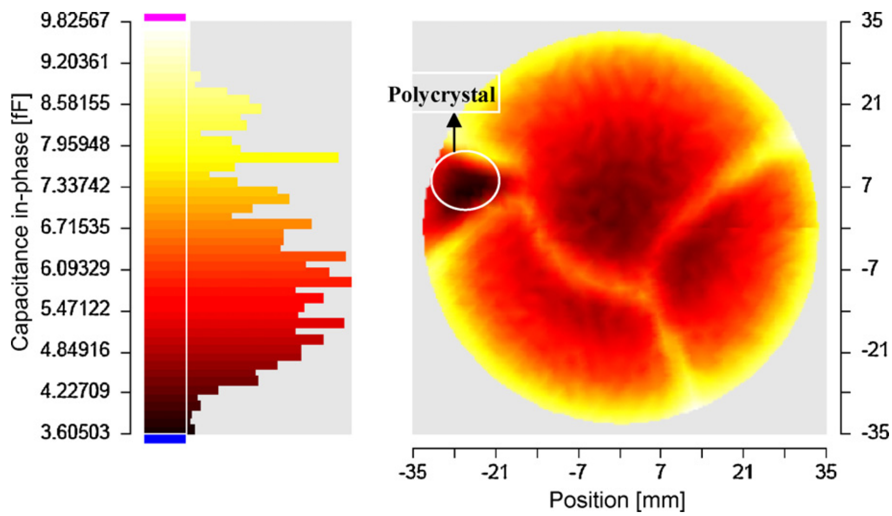

Fig. 3. Capacitance in-phase map of vanadium-doped 6H–SiC substrate with better surface.

is 19.83%, and we can find that crystal quality of this wafer is better than that of the one in Fig. 2, except for a part of polycrystal. In the other word, the homogeneity across the wafer shown in Fig. 3 is better than that shown in Fig. 2. With this method of capacitance measuring, we can observe the topography of V-doped substrate without troublesomely preparing sample for SEM or other testing techniques, and will not destroy the wafer and save time at some extent.

4. Conclusions

Complex surface capacitance mapping is demonstrated to be a capable technique for investigating the topography of V-doped SI substrate and relevant contributions of crystallization to resistance nonhomogeneity. Compared with sheet resistance mapping, the corresponding correlation between the capacitance quadrature and sheet resistance is found in vanadium-doped SI samples. Regions with low capacitance quadrature show high sheet resistance. This indicates, associated with the nonhomogeneity of sheet resistance on the substrate, that the quality of crystallization is not good enough, which also leads to resistivity nonhomogeneity when comparing with different types of deep defects. And according to the measured capacitance quadrature, we can also find that regions with a bad crystallization quality have a higher radio absorption coefficient. Another correlation is established between the capacitance in-phase and sheet resistance for the vanadium-doped sample. In this sample, the capacitance in-phase map shows not only the surface topography, but also the distribution trend as same as the sheet resistance, namely, regions of high capacitance in-phase reveal high sheet resistance.

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