Evaluation of Test Methods Employed for Characterizing Semi-Insulating Nature of Monocrystaline SiC Semiconductor Materials

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Abstract: Silicon carbide (SiC) substrates offer an attractive template for the development of gallium nitride-based semiconductor materials device technologies for the advancement of high power solid-state microwave and millimeter wave circuits in the commercial and military defense markets. To ensure that the resistivity specifications of semi insulating (SI) are accurately determined and reported, the SEMI North American SiC Task Force has completed a first round robin test activity which includes evaluating contact and non-contact test methods employed to report high resistivity values for SiC semiconductor materials. Results from the round robin are aligned with customer requirements for the development of a semi-insulating specification and test method for SiC substrates.

Introduction: In the recent years great strides have been made by the SiC community to increase the resistivity of semi insulating substrates above 10^5 ohm-cm range, generally considered as semi-insulating for more mature compound semiconductors materials technologies such as GaAs and InP substrates. Recent advancements have increased SiC substrate resistivity values and across wafer uniformities by several approaches including counter doping with a deep center forming metal such as vanadium[1] or by producing ultra high purity material with shallow level impurity concentrations below 10^{16} cm^{-3}[2]. High resistivity SiC substrates are rapidly moving towards high volume commercialization. In order to ensure that resistivity specifications are accurately determined and reported the SEMI North American SiC Task Force has completed a first round robin test activity evaluating contact [3] and non-contact [4,5] test methods employed to report high resistivity values for SiC semiconductor materials.

Experimental: The round robin study comprises a group of SiC substrate manufacturers, metrology tool vendors, university research centers, and a government research lab. SiC substrate vendors donated nine 3-inch diameter SiC wafers with resistivity values ranging from 10^4 to > 10^{12} ohm-cm as part of the study. The wafers were specifically selected to cover the entire measurement range of the metrology tools and they should not be considered representative of what is

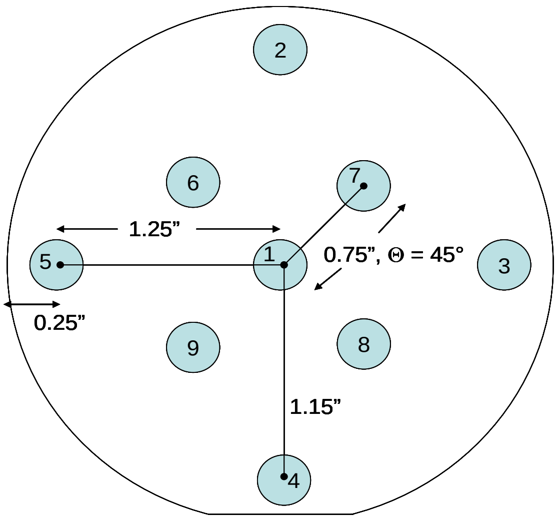

Figure 1: SiC substrate test site map used for resistivity round robin study

available for commercial sales from the vendors. Five groups conducted non contact (capacitance and microwave loss) measurements while two groups conducted contact (current voltage and Hall) measurements. To minimize variations in data reporting each test group performed measurements at nine sites aligned to the wafer map specified in Figure 1. It should be noted that the various measurement techniques evaluate resistivity either parallel or perpendicular to the c-axis and the data has not been corrected for any anisotropy of the resistivity. Also, ambient light levels and precise measurement temperatures at each laboratory have not been taken into account in this study.

Results: Data from the round robin are split into two groups. Group 1, shown in Figure 2, contains data from wafers with resistivity levels mostly at or below 1x10^8 Ω-cm. In these graphs circles (dark and light blue)) and squares (pink and yellow) are the same non contact techniques utilized at different laboratories. Variations in the resistivity levels over several orders of magnitude are

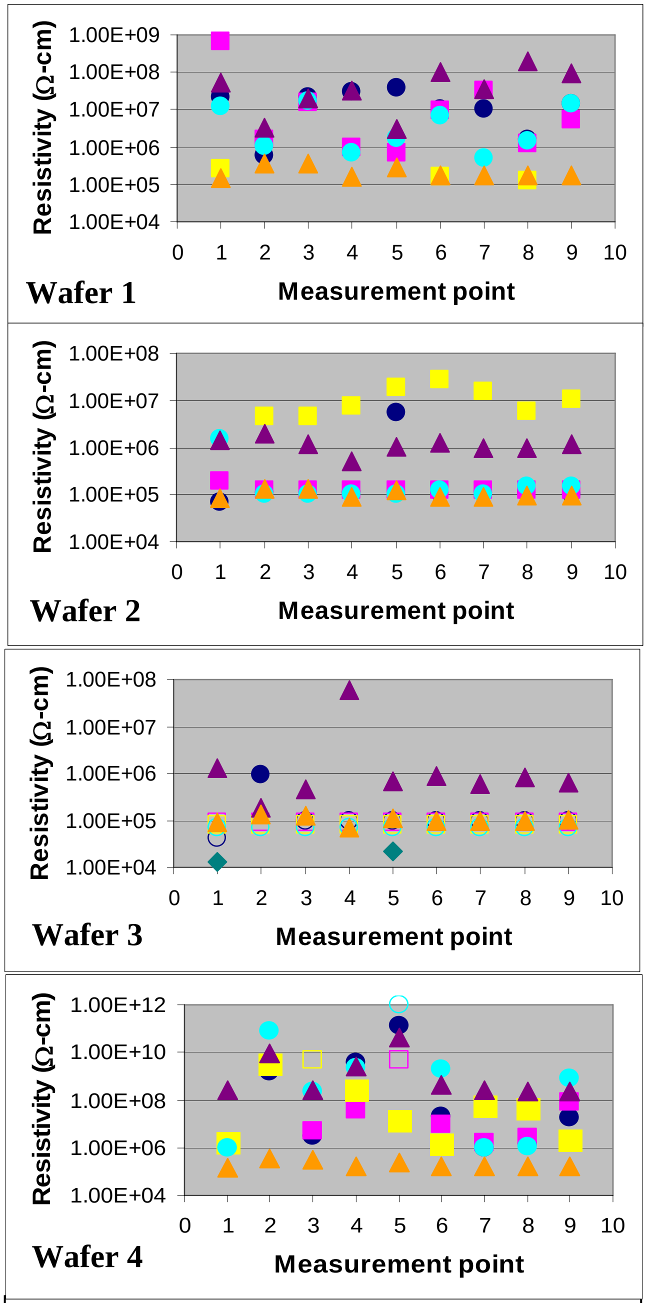

Figure 2: Resistivity data for Group 1 wafers mostly below 1x10^8 Ω-cm. Symbols for measurement techniques are as follows: Circles (2 colors) and squares (2 colors) are non contact techniques from 2 different vendors, purple triangles are an IV based technique orange triangles are a microwave loss technique, and green diamonds are Hall measurements. Open symbols indicate values above and below the tool range.

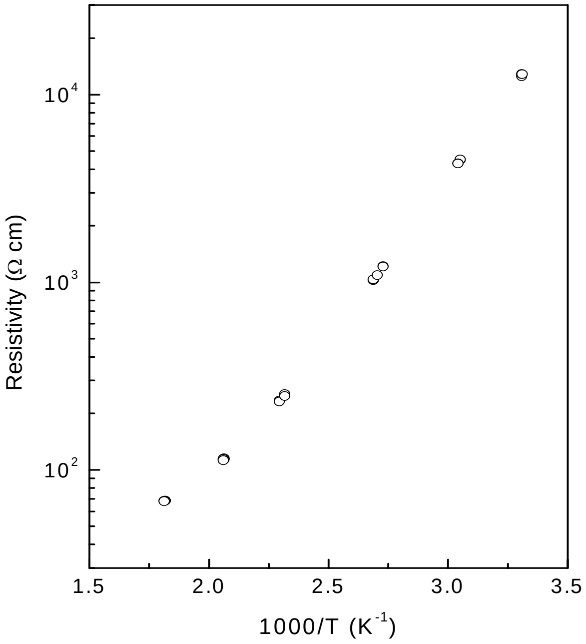

Figure 3: Arrhenius plot of temperature dependent Hall data for wafer 3 point 1 of the low resistivity set of wafers. Room temperature value for resistivity = 1.3 E4 Ω-cm

observed in the data set, even from sets of measurements made with the same techniques at different laboratories. Temperature dependent Hall measurements were also performed on points 1 (see Figure 3) and 5 of wafer #3. Resistivity values from the Hall measurements on wafer 3 also show low resistivity values. The reasons for any potential variation in resistivity values across the wafers is beyond the scope of this paper, but there are significant differences in the measured values of the same points on the same wafers as measured by different laboratories utilizing similar tools. The root cause of this variation for the lower resistivity ranges is not clearly understood at this time.

The second group of data, shown in Figure 4, is from wafers that had most of their resistivity levels at or above 1×10^9 Ω-cm. Again, in these charts circles (dark and light blue)) and squares (pink and yellow) are the same non contact techniques utilized at different laboratories. The microwave

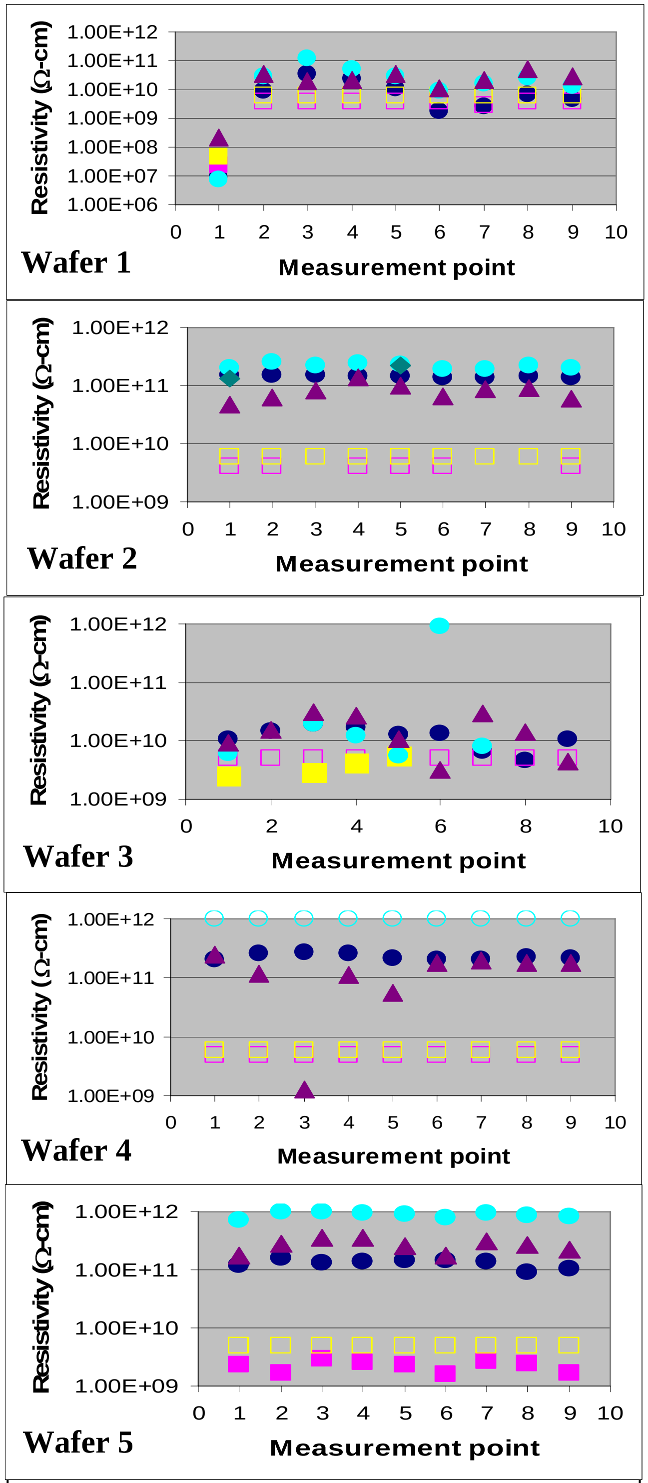

Figure 4: Resistivity data from wafers with the majority of measurements at or above 1×10^9 Ω-cm. Symbols represent the same measurements as in Figure 2. Open symbols indicate values above the tool maximum

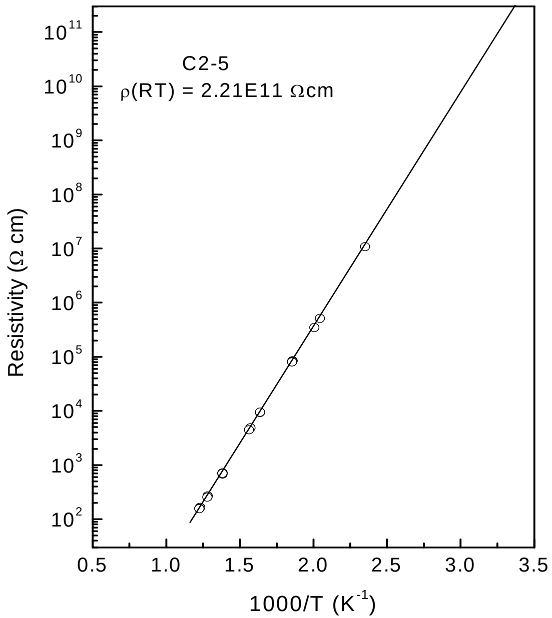

Figure 5: Arrhenius plot of temperature dependent Hall data for wafer 2 point 5 of the high resistivity set of wafers. Room temperature extrapolated value for resistivity = 2.2 E11 Ω-cm

loss technique is above its maximum value, and this data was not included in Figure 4. For this set of measurements an added complication was that the non contact measurement technique represented by squares has a maximum resistivity range of ~ $5x10^9$ Ω-cm. The upper range for the non contact measurement technique represented by circles is $1x10^{12}$ Ω-cm. The upper range for the contact measurement technique, represented by purple triangles, is potentially higher. Therefore there is no real disagreement between groups in this data set as was seen in the lower resistivity range data. Given the equipment limitations, the data for the high resistivity samples are in generally good agreement with all measurement techniques at the tool maximum or measuring above $5x10^9$ Ω-cm.

Temperature dependent Hall measurements [1,2] have been made on point 5 of wafer 2. An Arrhenius plot of the data is shown in Figure 5. The room temperature value of the resistivity shown on Figure 4 for the Hall measurement is obtained by extrapolation. This measurement confirms the high resistivity of the point sampled in wafer #2 and the extrapolated room temperature value is in agreement with the other data measured.

Summary: The SEMI North American SiC Task Force has completed a first round robin test activity for resistivity measurements of semi insulating silicon carbide. Both 4H and 6H polytypes were included in the study and resistivity ranging from below $1x10^5$ Ω-cm to above $1x10^{12}$ Ω-cm was measured with both contact and non-contact techniques. The data for the high resistivity samples (> $1x10^9$ Ω-cm) are in generally good agreement with all measurement techniques at the maximum of the tool or measuring within one order of magnitude of each other. The data for the low resistivity samples (< $1x10^8$ Ω-cm) show variations in the resistivity levels over several orders of magnitude, even from sets of measurements made with the same techniques at different laboratories. Further work will be required to understand this variation.

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Acronyms

SiC: silicon carbide

SI: semi insulating