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Four-point probe characterization of 4H silicon carbide

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ABSTRACT

We report on four-point probe measurements on SiC wafers as such measurements give erratic data. Current–voltage measurements on n-type SiC wafers doped to 3×10^{18} cm^{-3} are non-linear and single probe I–V measurements are symmetrical for positive and negative voltages. For comparison, similar measurements of p-type Si doped to 5×10^{14} cm^{-3} gave linear I–V, well-defined sheet resistance and the single probe I–V curves were asymmetrical indicating typical Schottky diode behavior. We believe that the reason for the non-linearity in four-point probe measurements on SiC is the high contact resistance. Calculations predict the contact resistance of SiC to be approximately 10^{12} Ω which is of the order of the input resistance of the voltmeter in our four-point probe measurements. There was almost no change in two-probe I–V curves when the spacing between the probes was changed from 1 mm to 2 cm, further supporting the idea that the I–V characteristics are dominated by the contact resistance.

1. Introduction

Four-point probes are routinely used for semiconductor material characterization [1]. Most commonly they measure the sheet resistance of thin conducting layers and wafers. Their advantage, compared to two-point probes, lies in the way the current and voltage are measured. As shown in Fig. 1 for an in-line four-point probe configuration, the current (probes 1 and 4) and the voltage (probes 2 and 3) are measured with different probes. The equivalent circuit shows the probe resistance (R_{pr}), the contact resistance (R_c) and the semiconductor resistance (R_s). The key advantage of four-point probe or Kelvin measurements is that due to the high input impedance voltmeter drawing very low current, the contact resistances of probes 2 and 3 usually play a negligible role in the measurements.

In contrast to two-probe measurements, where the current flows into probe 1 and out of probe 4 with the voltage measured across these same two probes, in four-point probes the measured current I flows through contacts resistances R_{cc}, but voltmeter current I_V flows through contact resistances R_{cv}. Hence, the measured voltage V is different from the actual semiconductor voltage V_S. Of course, current I is much higher than current I_V making $V \approx V_S$, but this depends on I_V and the various resistances. Hence the contact resistance, which is likely current dependent, may be different for contacts 1–4 (R_{cc}) than for contacts 2–3 (R_{cv}).

Four-point probe measurements of the more common semiconductors, Si, Ge, GaAs, yield accurate results. Such is not the case for the wide band gap semiconductor SiC. Consequentially, such measurements are typically not used to characterize SiC. Instead, the non-contact Eddy current method is used. The published literature on SiC four-point probe measurements is quite sparse. A few SiC four-point probe measurements have been reported. Muzykov et al. measured semi-insulating SiC wafers with resistivities in the 10^9–10^{11} Ω cm range [2]. These measurements were made with removable graphite contacts in a square arrangement by applying graphite paint using a sharpened wood tip. Samples were also made with diffused- and annealed-metal contacts. The graphite contact samples showed distinctly diode-like I–V behavior. Since the resistivity is so high in these samples, it is not obvious what role contact resistance played in these measurements. Siergiej et al. measured highly-doped SiC wafers (0.007 Ω cm) with four-point probes, but for more resistive samples they used the Eddy current method [3]. Others used deposited metal contacts in a four-point probe configuration, but usually annealed these contact for reduced contact resistance [4]. Weishart et al. mention the use of four-point and van der Pauw measurements, but give no details [5]. Golecki et al. mention briefly that they measured the resistivity of epitaxial cubic SiC films grown on Si substrates with no further detail [6]. Katulka et al. characterized Ge implanted 4H–SiC with four point probes. Other than mentioning the measured sheet resistance, they give no further information [7]. We have found four-point probe measurements on SiC to give nonsensible results.

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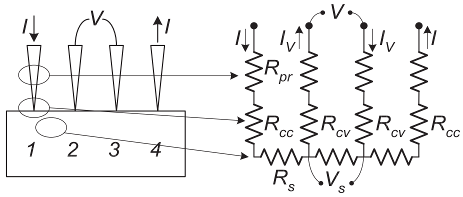

Fig. 1. In-line four-point probe configuration.

2. Experimental

Our samples consisted of n-type 4H–SiC wafers with the off-axis cut at 4° towards $[11\bar{2}0]$. Wafer resistivities, determined by Eddy current measurements (SemiLab WT-2000), ranged from 0.018 to 0.023 Ω cm ($N_D \approx 2$–3×10^{18} cm^{-3}) at wafer thicknesses of about 375 μm. The four-point probe measurements were made with a Signatone S 302-8 with 1 mm tip spacing, 85 g spring pressure, tungsten carbide tips with 125 μm tip radii. The Keithley 2400 voltmeter of this probe system has an input resistance of $>10^{10}$ Ω. The one- and two-probe measurements were made with an Agilent 5600 system.

The inability to use four-point probes for SiC is not obvious. After all, contact resistances of the voltage probes are not supposed to play a role during such measurements. We show in Fig. 2 SiC four-point probe current–voltage measurements. While such data for Si show a nice straight line as expected, the SiC data are clearly very non-linear. This non-linearity holds for a range of currents as indicated with all curves being distinctly non-linear and some even exhibiting negative resistance regions. To see if the Si-face is different than the C-face, we show in Fig. 3 data for both faces. The *I*–*V* data are distinctly non-linear for both, with the C-face exhibiting higher currents. We have observed this in all four-point probe measurements.

To try to clarify this puzzle, we made one- and two-probe measurements. For the one-probe measurement, the probe was placed on the sample surface with the probe chuck providing the bottom contact. For the two-probe measurements, both probes were placed on the sample top surface. For these measurements we varied the probe spacing from 1 mm to 2 cm. Fig. 4 shows the current voltage characteristics of one sample. Other samples behave similarly. The voltage refers to the probe voltage. The curves are distinctly non-linear, but do not exhibit Schottky diode behavior as one might expect from metal probe/semiconductor devices. Furthermore, the curves for the two probe setups are similar to one-probe measurements. To check whether the carbon or the silicon faces behave differently, we show in Fig. 5 the data in both linear and semi-log plots. In the semi-log plot, the negative current was made positive for the log plot. It is obvious from these curves that the two faces exhibit essentially the same *I*–*V* behavior with the C-face showing slightly higher currents for positive voltages.

The four-point voltage probe contact resistance may play an important role in SiC four-point probe measurements since the barrier height of the metal/semiconductor contact is very high, probably 1–1.5 eV. For this reason we have extracted the differential resistance of the devices in Fig. 4. The resulting data are shown in Fig. 6. The two-probe data are asymmetric. However, for other samples similar data are reasonably symmetric. The values peak around zero voltage with very high values in the 10^7–10^8 Ω range. This is consistent with the four-point probe data in Fig. 3, that exhibit the highest non-linearity around zero volts, where the contact resistances are highest.

For comparison, we show in Fig. 7 four-, and one-point probe and differential resistance data for Si wafers. The four-point probe data in Fig. 7c show strictly linear behavior for the two wafers with widely different resistivities. The one-probe data indicate typical Schottky diode behavior with conduction in the forward and very low current in the reverse direction in Fig. 7a and b. The turn-on voltage, however, is much higher than typical Si Schottky diodes, which is due to the point contact of the mechanical probe. With both forward and reverse current being low, the differential resistance is quite high in Fig. 7d. It is even higher

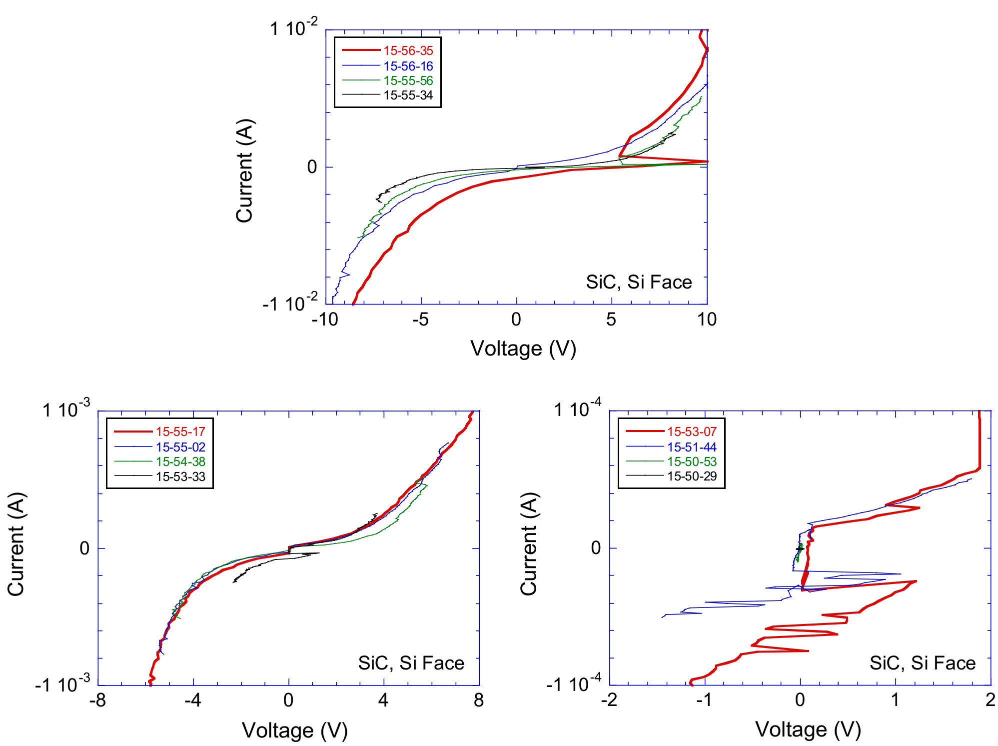

Fig. 2. SiC four-point probe current–voltage data for three current ranges.

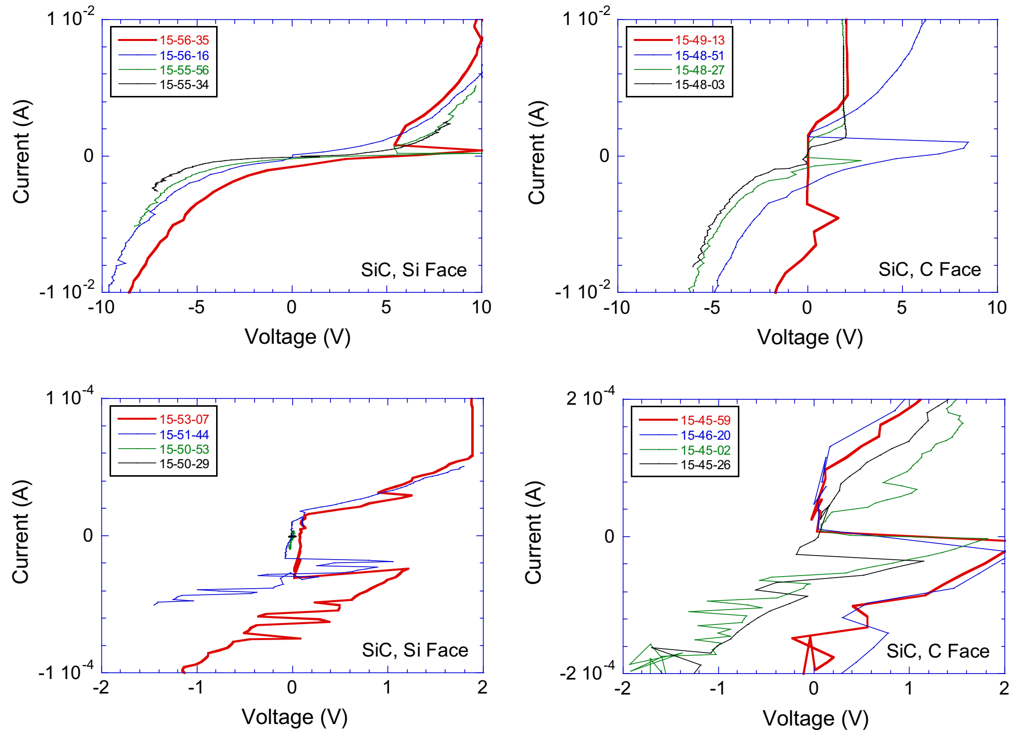

Fig. 3. SiC four-point probe current–voltage data for silicon and carbon faces.

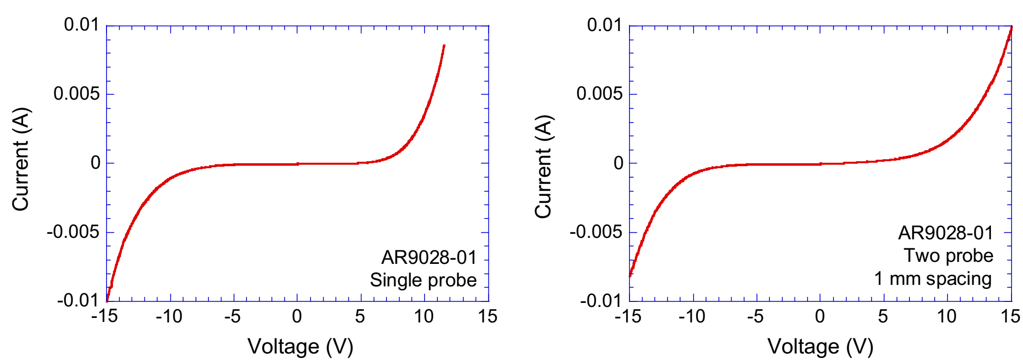

Fig. 4. SiC one-probe and two-probe current–voltage data.

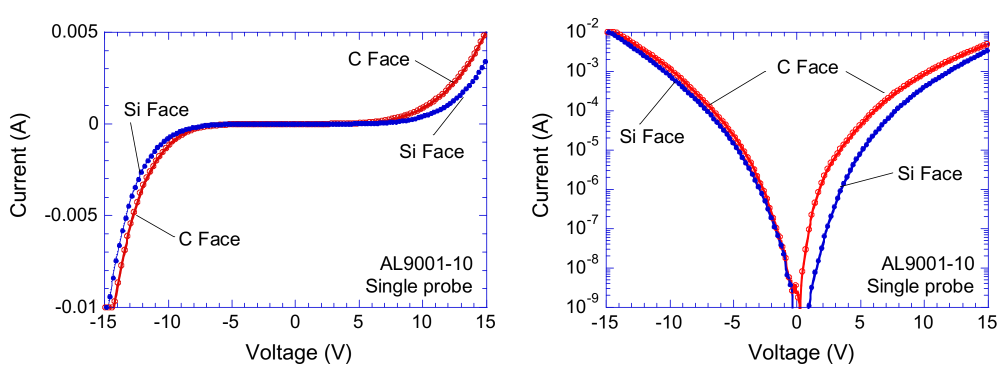

Fig. 5. SiC current–voltage plots for the carbon and silicon faces.

than the SiC values in Fig. 6. It should be mentioned that while the probe pressure in the four-point probe measurements is well controlled, such is not the case for the one- and two-probe measurements. The latter were made in a conventional probe station and the probe pressure is determined by the operator's adjustment. Hence, contact resistances, which depend on probe pressure and probe contact area, are likely to be different for these measurements.

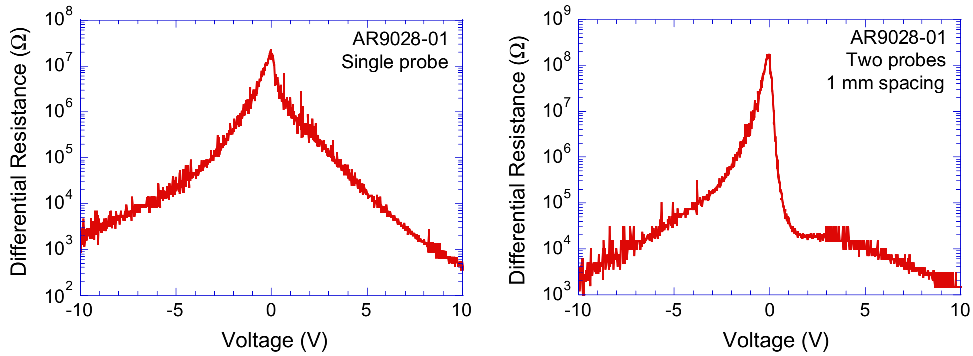

Fig. 6. SiC differential resistance for the sample of Fig. 4.

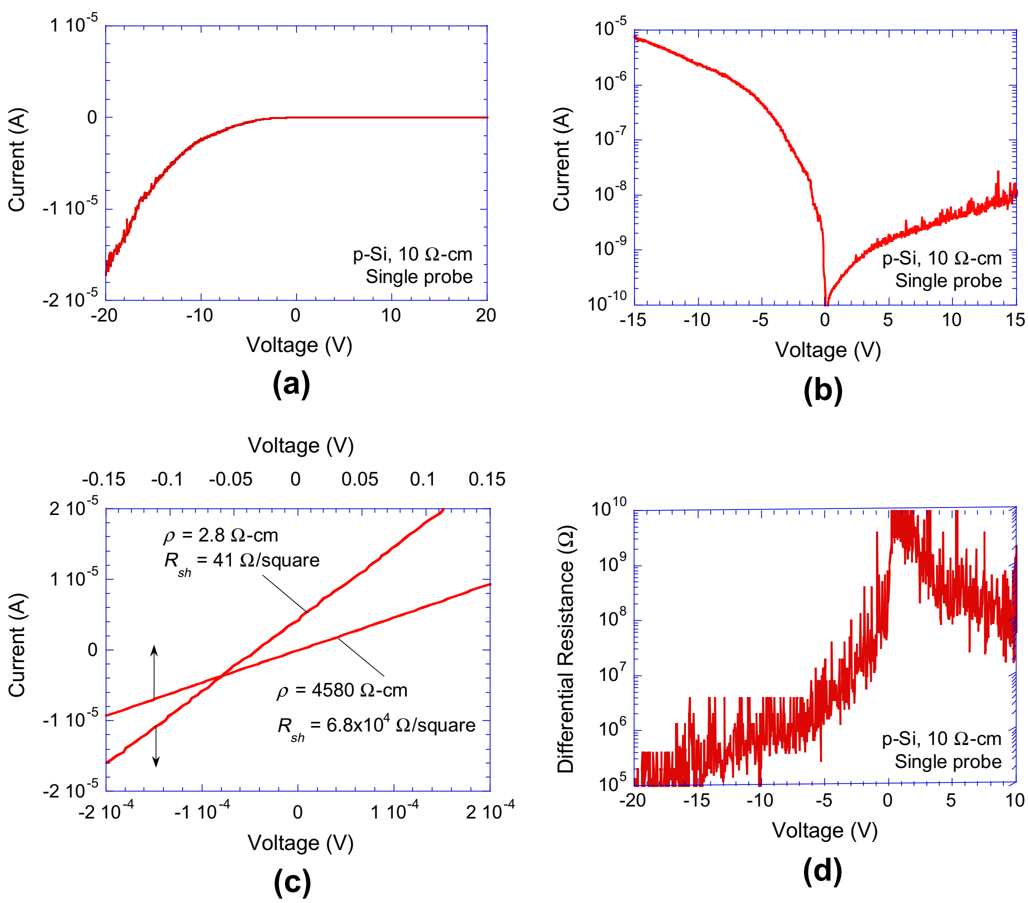

Fig. 7. Silicon (a and b) single-, (c) four-probe current–voltage and (d) differential resistance.

Comparing the Si and SiC data taken with the same measurement equipment clearly shows the SiC samples to behave very differently.

3. Discussion

The SiC *I–V* behavior is not that of typical point probe Schottky diodes. Instead the curves are fairly symmetrical for positive and negative voltages. Furthermore the one- and two-point probe measurements are similar and changing the probe spacing in the two-probe measurement from 1 mm to 2 cm hardly changes the *I–V* characteristics, suggesting that the *I–V* behavior is dominated by the contacts and is not thermionic emission limited. Thermionic-limited *I–V* would exhibit typical non-linear characteristics with very different forward and reverse *I–V* behavior. Instead it appears to be thermionic-field current which is consistent with the fairly high doping concentrations ($N_D \approx 2\text{–}3 \times 10^{18}\ \text{cm}^{-3}$) of these wafers. Tunneling or field emission currents would be more linear with lower voltage offsets than thermionic-field current. Trying to fit theoretical curves to the experimental data is fraught with difficulties since we know neither the contact area, nor the contact resistance nor the barrier height. Nevertheless, we followed the specific contact resistivity, ρ_c, calculations of Yu [8] and Ng and Liu [9]. Their equations predict Si ρ_c quite well. For Si at room temperature with $N_D = 5 \times 10^{14}\ \text{cm}^{-3}$ ($\rho = 10\ \Omega\ \text{cm}$),

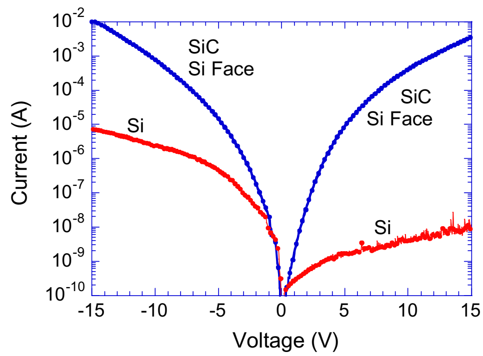

Fig. 8. *I–V* of devices in Figs. 5 and 7.

$n_i = 10^{10}$ cm^{-3} and barrier height $\phi_B = 0.6$ eV, the current in a metal–Si contact is thermionic current with $\rho_c \approx 30\ \Omega\ \text{cm}^2$ and for $N_D = 3 \times 10^{18}$ cm^{-3} the current is thermionic-field current with $\rho_c \approx 1\ \Omega\ \text{cm}^2$. Similar calculations for 4H–SiC with $N_D = 3 \times 10^{18}$ cm^{-3}, $n_i = 1.4 \times 10^{-8}$ cm^{-3}, $\phi_B = 1.2$ eV and $E_G = 3.23$ eV, yields $\rho_c \approx 10^8\ \Omega\ \text{cm}^2$. We base this ϕ_B value on our earlier Mo–SiC Schottky diode measurements, yielding $\phi_B \approx 1.2$ eV from *I–V* and 1.6 eV from *C–V* measurements [10]. The contact resistance, R_c, depends on contact area which is poorly known for the two-point probe measurements and is very sensitive to the barrier height which is also not well known. Our probes have radii of ~1 μm leading to $R_c \approx 3 \times 10^9\ \Omega$ for the 10 Ω cm Si samples, in approximate agreement with the data in Fig. 7. A similar calculation for SiC yields $R_c \approx 10^{16}\ \Omega$ – very different from Fig. 6.

For the four-point probe measurements, we use tungsten-carbide probes with 125 μm radii and 85 g pressure. These probes/pressure are likely to approximate a Schottky contact, with the current governed by thermionic emission for the $N_D = 5 \times 10^{14}$ cm^{-3} Si and thermionic-field emission for the 3×10^{18} cm^{-3} SiC. Now the contact resistance becomes $R_c \approx 3 \times 10^5\ \Omega$ for the 10 Ω cm Si, for an effective contact area of 10^{-4} cm^2. This contact resistance is much lower than the voltmeter input resistance. For the SiC samples this yields $R_c \approx 10^{12}\ \Omega$ – on the order of the voltmeter input resistance. For such high contact resistances, the usual assumption of contact resistance being negligible compared to voltmeter input resistance in four-point probe measurements is no longer satisfied. For the 0.007 Ω cm SiC wafers of Siergiej et al. [3] we predict $\rho_c \approx 0.1\ \Omega\ \text{cm}^2$. These wafers apparently gave valid four-point probe data which is not surprising given the low ρ_c. But even they did not use four-point probe measurements for the more resistive samples.

To compare the *one-probe I–V* behavior, we show in Fig. 8 the Si and SiC data of Figs. 5 and 7. Clearly, the SiC currents are much higher for all voltages, positive and negative. This suggests that series resistance (contact resistance) is actually lower for SiC, which is consistent with the higher SiC doping concentration and very likely different current mechanism than the Si wafer: thermionic for Si and thermionic-field for SiC. That is also evident from the almost symmetrical SiC and distinctly asymmetrical Si *I–V* data. Yet the SiC four-point probe measurements exhibit unconventional behavior.

4. Summary

We have characterized the four-point probe behavior of Si and SiC wafers. As observed by others, we find such measurements not to be suitable for SiC, even though it is routinely used for Si and other semiconductors. Based on a series of measurements and contact resistance calculations we propose that the extremely high contact resistances of the probe–SiC contacts make four-point probe sheet resistance measurements fraught with difficulty for lightly- to moderately-doped samples. For heavily-doped samples with $N_D > 2 \times 10^{19}$ cm^{-3}, such measurements should work with little problem, as ρ_c is below ~100 Ω cm^2.

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