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Characterization of Silicon Carbide

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Abstract

The first semiconductor devices were created using silicon carbide. Research into local effects began with silicon carbide. Since local effects manifest primarily at contacts, control studies were conducted on both the bulk properties of silicon carbide single crystals and their surfaces, as well as on the effects in silicon carbide determined by its particle size. This comprehensive study allowed us to determine the nature of polytype formation in silicon carbide and provide practical recommendations for producing perfect silicon carbide samples and adjusting the current-voltage characteristics of silicon carbide devices.

Keywords: Silicon carbide; Contact thermoelectric effects; Phonons; Polytypes; Charge density waves

Introduction

Silicon carbide can be considered the first semiconductor. Even before Quantum Mechanics introduced the concept of a semiconductor, in 1907, Henry Joseph Round created the first LED by applying voltage to SiC crystals and observing yellow, green, and orange radiation at the cathode. Although Max Planck had already obtained the correct formula for the energy distribution in the spectrum of a blackbody by the end of 1900 and provided its theoretical justification by introducing the famous "quantum of action," and the photoelectric effect was explained in 1905 by Albert Einstein, the active implementation of Quantum Mechanics in solid-state physics had not yet occurred.

Round's experiments were repeated on silicon carbide by O.V. Losev in the USSR in 1923. But he also anticipated Quantum Mechanics by introducing the concept of different types of electron conductivity-in effect, he discovered what is now called a hole in semiconductor physics. Furthermore, Oleg Losev created the first semiconductor device using SiC crystals of various colors-the Resistance Transformer, an abbreviated English translation of which, from Losev's article, was used by Nobel laureates to name the Transistor.

Silicon carbide [1], due to its hardness and resistance to various mechanical and chemical influences, was initially used primarily as an abrasive material and was significantly inferior to other semiconductors. But for these same criteria, coupled with its high thermal stability, SiC began to be used for high-power microwave diodes and thyristors.

And, like Losev, I conducted my first experiments in 1980 to detect localized thermo-EMF at contacts using calibrated abrasive SiC powders.

Although, for control purposes, I studied ground SiC single crystals grown in Yuri Vasilyevich Vodakov's laboratory. The powders, ground to calibrated sizes by Vitaly Petranovsky, were then used to study size effects in the kinetic characteristics of semiconductors (Figure 1).

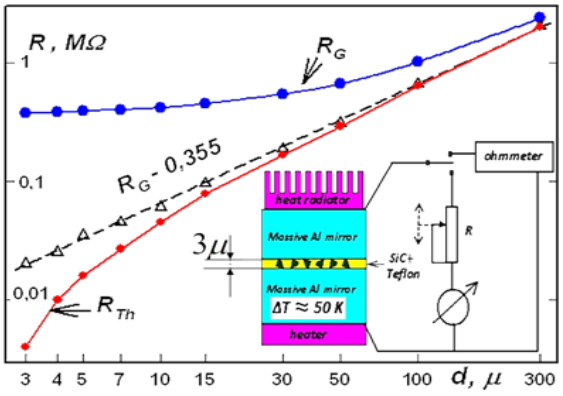

Figure 1: *Reduction of the output, generator thermoelectric resistance with a decrease in the size of SiC crystals to 3 μm [2].*

As further studies have shown, the effects arising in the contact region cannot be attributed to small corrections [3, 4]. These local effects manifested themselves not only in the generation of anomalously large thermo-EMF. As studies of contact effects on unpackaged diodes based on silicon carbide from the company "Krii" have shown, when current flows, not only blue light but also a measurable heat flux emerges from under the thin upper gold contact. The main heat discharge from the thermally insulated thin gold contact occurred through the measuring micro-thermocouple. Moreover, in the initial section of the I-V characteristic, an increase in current was observed with an increase in the recording time (Figure 2a). And this indicated an increase in the contact

temperature, which was confirmed by its direct measurements (Figure 2b). Thus, an analogue of the inverse thermoelectric effect - the Peltier effect - was reliably recorded at the silicon carbide contact.

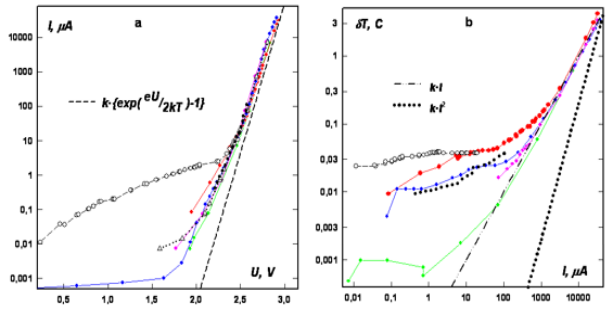

Figure 2: *Forward branches of the I-V characteristics of a p-i-n structure at different thermal stabilization times (a) and the corresponding temperature differences δT occurring across the structure (b).*

Measurements were also performed on Japanese SiC powders with a grain size of 0.15 μm, but using the method shown in Fig. 1, without an insulating Teflon layer due to short circuits, reliable, repeatable thermoelectric data could not be obtained. The results of IR spectral studies of sintered and pressed samples made from 0.15 μm powder are shown in Figure 3 and in [5].

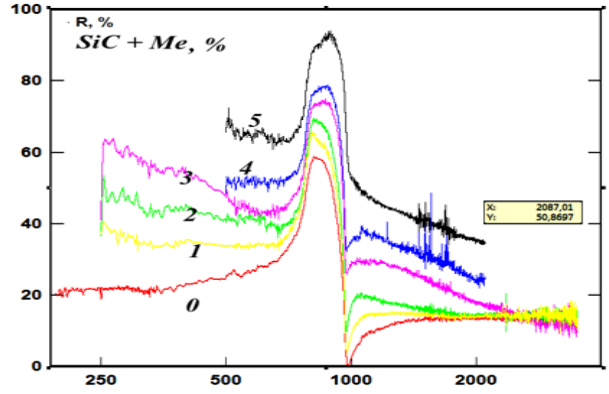

Figure 3: *IR spectra in the lattice reflection region of silicon carbide samples pressed and sintered from nanopowder with different metal concentrations.*

In this case, precision, calibration polarization IR spectral studies of the initial SiC single crystals were carried out (Figure 4).

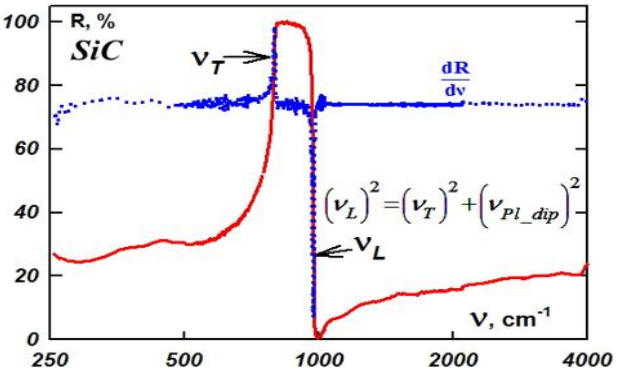

Figure 4: *Lattice oscillator characteristic of hexagonal silicon carbide phases.*

Hexagonal silicon carbide phases exhibited a virtually identical lattice oscillator when reflected from a plane perpendicular to the C-axis. For polarization along the C-axis, a slight softening of the lattice oscillator-a slight shift toward lower frequencies-was observed.

Ion implantation is widely used in the fabrication of silicon carbide devices to alter the free carrier concentration.

Ion implantation into the surface layer of SiC single crystals showed that the frequencies of characteristic phonons are strictly preserved (Figure 5).

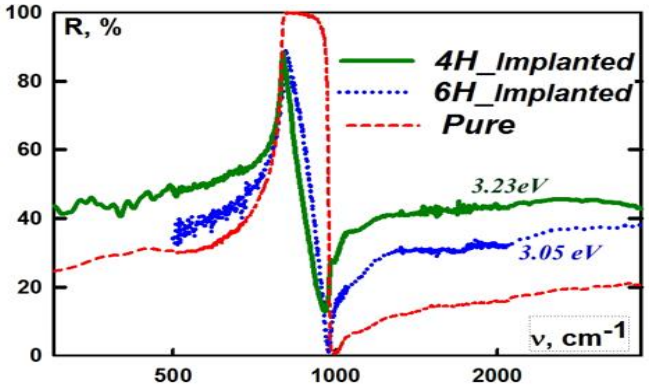

Figure 5: *Changes in lattice oscillators on the implanted surface of hexagonal silicon carbide single crystals.*

However, as can be seen from Figure 5, changes in these oscillators occur not due to free carriers, but due to an increase in high-frequency permittivity.

The characteristic concentrations of implanted ions, which were believed to uniquely determine the carrier concentration, are relatively low (Figure 6).

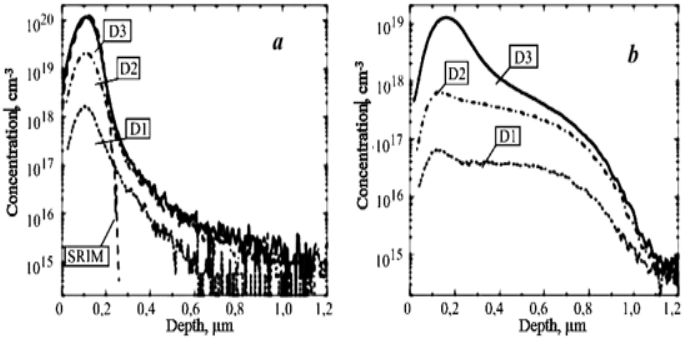

Figure 6: *Concentration profiles of 100 keV aluminum implanted in SiC at room temperature with three different doses (D1 < D2 < D3): a-random implantation; b-channeling implantation (ion beam incidents normally occur on the (0001) plane) [6].*

That is, the carrier concentration in silicon carbide, given its low mobility, is insufficient to generate powerful, high-frequency plasma effects. Therefore, the increase in the high-frequency reflectivity in Figure 3 is determined by the increase in the refractive index, indicating a decrease in the band gap. Layer-by-layer removal of several microns of implanted material leads to complete restoration of the lattice oscillator shape (Figure 7).

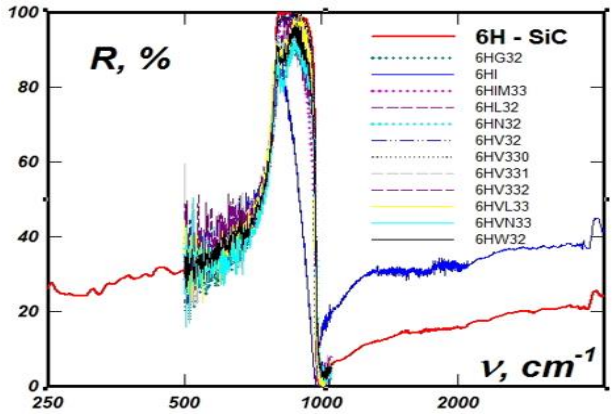

Figure 7: *Complete restoration of the lattice oscillator of a silicon carbide single crystal after removing a layer several microns thick from the implanted surface.*

From the conservation of the transverse photon frequency, it follows that the lattice rigidity remains virtually unchanged upon implantation, and from the conservation of the longitudinal phonon frequency, the charge of its dipole remains virtually unchanged. Thus, implanted ions primarily produce interstitial defects, which create additional, excess pressure, leading to a change in the electron band structure and a change in the band gap. Meanwhile, the surface of a pure single crystal has excess pressure in the form of surface tension, and this, and not just the Schottky barrier, must also be taken into account in device design.

For pure (undoped) perfect Vodakov single crystals, all of its hexagonal phases, when reflected from a plane perpendicular to the C axis, as shown previously, produced a virtually identical oscillator with characteristic transverse and longitudinal phonon frequencies (Fig. 2). Combined with studies of the frequency dependence of the lattice reflection maximum of single-crystal silicon carbide powders and nanoparticles, which corresponds to a transverse phonon, a general picture can be obtained (Figure 8).

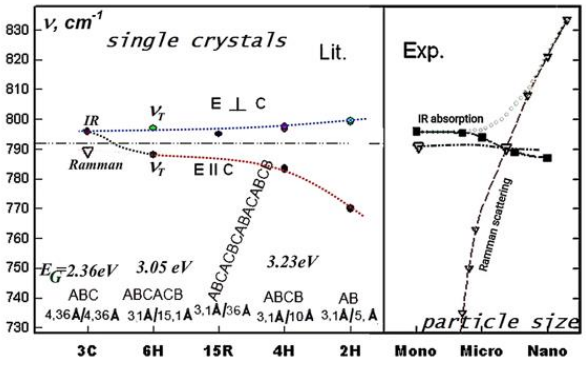

Figure 8: *Schematic representation of resonance frequencies. Left: frequencies of transverse optical phonons of single crystals of different SiC polytypes according to literature data, top-for E perpendicular to the C axis, bottom-for E parallel to the C axis (triangles-Romanov scattering). Right: Dependence of the frequency of the lattice IR absorption maximum in bulk samples on the particle size and their Romanov scattering (which produces a large spread due to the diffraction of the exciting light wave [5].*

The resulting composite picture again raises the question of polytheism in silicon carbide. It does not lead to the folding of the Brillouin zone for phonons - only the weak changes within the elementary crystal lattice shown in Figure 6 are observed, and not the superstructural division of the frequencies of characteristic phonons. Therefore, X-ray patterns producing a superlattice could be mistaken for parasitic moiré. However, the features revealed in the implantation indicate the possibility of the initial formation of superordered pressure regions in silicon carbide single crystals, leading to modulation of the band gap and, thus, to charge density waves. It follows that polytypes are simply different charge density waves. And charge density waves are, naturally, transparent to Phonons, which are determined by the displacement of ions whose masses are thousands of times greater than the electron's mass. Therefore, the differences in the crystal structures of the polytypes are fictitious-X-rays simply captured the alternation of regions of compression and tension in the crystal lattice.

Practical recommendation: it is advisable to anneal silicon carbide samples under hydrostatic pressure in silicone oil at 20 kbar.

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