

SiC Mass Commercialization: Present Status and Barriers to Overcome

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Keywords: SiC, substrate, epitaxy, fabrication, etch, heated implantation, Ohmic contact, silicide, SiC fab infrastructure, SiC foundry, fabless, basal plane dislocations, bipolar degradation, 200 mm

Abstract. In an increasingly electrified technology driven world, power electronics is central to the entire clean energy manufacturing economy. Silicon (Si) power devices have dominated power electronics due to their low cost volume production, excellent starting material quality, ease of fabrication, and proven reliability. Although Si power devices continue to improve, they are approaching their operational limits primarily due to their relatively low bandgap, critical electric field, and thermal conductivity that result in high conduction and switching losses, and poor high temperature performance. Silicon Carbide's (SiC) compelling efficiency and system benefits have led to significant development efforts over the last two decades and today planar and trench MOSFETs, and JFETs are commercially available from several vendors as discrete components or in high power modules in the 650 V to 1700 V voltage range. High impact application opportunities, where SiC devices are displacing their incumbent Si counterparts, have emerged and include automotive and rail power electronics with reduced losses and reduced cooling requirements; novel data center topologies with reduced cooling loads and higher efficiencies; variable frequency drives for efficient high power electric motors at reduced overall system cost; more efficient, flexible, and reliable grid applications with reduced system footprint; and "more electric aerospace" with weight, volume, and cooling system reductions contributing to energy savings. In particular, SiC insertion in electric vehicles brings major competitive advantages and is a volume application opportunity that can spur manufacturing economies of scale and lower system costs. As SiC continues to grow, the industry is lifting the last barriers to mass commercialization that include higher than Si device cost, relative lack of wafer planarity, the presence of basal plane dislocations, reliability and ruggedness concerns, and the need for a workforce skilled in SiC power technology to keep up with the rising demand. It should be noted that in many applications, insertion of SiC reduces overall system cost compared to Si even though SiC devices can cost 2-3 more than their Si counterparts. This is due to the passive component and cooling system simplifications enabled by the efficient high frequency SiC operation. In this paper, we will review key aspects of SiC technology and discuss overcoming barriers to mass commercialization.

SiC Wafers

Today, the SiC wafer represents 55-70% of the overall SiC device cost [1], a consequence of its unique complex fabrication specifics. Conventional SiC substrates are primarily grown by the seeded sublimation technique at temperatures of ~2500 °C, which creates process control challenges. Crystal expansion is limited requiring the use of large high-material quality seeds, and the sublimation growth rates can be relatively low in the order of 0.5-2 mm/h. Dislocations propagate through the boule and are present in the device wafers. Furthermore, SiC material's hardness, which is comparable to that of diamond, makes sawing and polishing SiC substrates slow and costly relative to Si.

The epitaxial layers, where SiC devices are fabricated, are grown by chemical vapor deposition (CVD) in horizontal or planetary reactors at 1500-1650 °C. Pressure typically ranges from 30 to 90 Torr and growth rates can be as high as 46 mm/hr. Epitaxial growth is done on 4-degree off-cut substrates to maintain the polytype stability of the substrate. Epitaxy goals are to restrict "performance-degrading" defect propagation from the substrate into the epitaxy and ensure that any "performance-degrading" defects propagating from the substrate propagate as benign defects into the

epitaxy. As defects in SiC wafers limit large-area device yields, and numerous devices are paralleled in modules to increase current output, tight epitaxial doping and thickness uniformities are highly desirable, particularly as wafer size increases. Fig. 1 shows a JFET pinch-off voltage map (a parameter that depends on doping) of an 84.3% overall yield wafer [2]. The screening parameter ranges appear in the top table. The pinch-off voltage screening ranges appear in the bottom table. “Failed” JFETs appear in gray and are primarily located at the wafer edges. The 84.3% yield includes the contribution of devices located at the wafer edges. The large uniformly situated white squares contain experimental devices and characterization structures. Each color-coded wafer area corresponds to JFETs with pinch-off voltages within the range shown in the bottom right table. The “bull’s eye” structure (concentric circular regions of different colors) correlates well with the measured radial doping variation in the epitaxy of this “older generation” 3-inch 4H-SiC wafer. The radial doping variation renders “outer” devices out of specification and lowers yields.

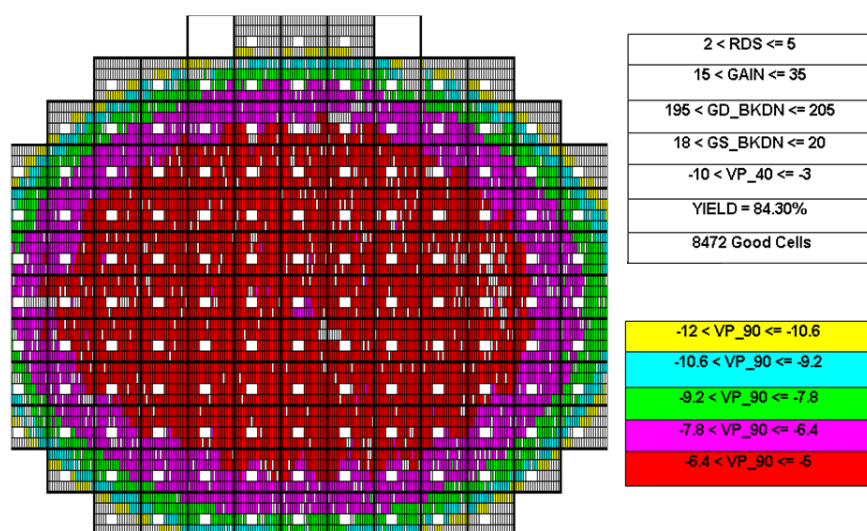
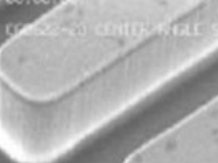


Fig. 1. JFET pinch-off voltage wafer map. “The “bull’s eye” structure (concentric circular regions of different colors) correlates well with the measured radial doping variation in the epitaxy of this “older generation” 3-inch 4H-SiC wafer. The screening parameter ranges appear in the tables.

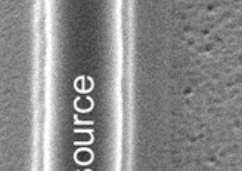
Overall, SiC wafer fabrication is more complex and slower than that of silicon. The result is more expensive wafers, and ultimately higher device costs. A key part of the vertical integration occurring in today’s SiC industry is securing internal substrate and epitaxy wafer capabilities to eliminate purchasing profit margins. In addition, opportunities for disruptive SiC substrate formation, boule slicing, sawing/polishing, etc., have a high return and are being sought by several companies [3].

Presently, the majority of SiC device production is on 150 mm wafers. 200 mm SiC wafers were demonstrated in 2015, and a seven-year or so period historically passes before they become available as products. It is highly desirable that defect density and the cost of material per cm^2 are the same or lower for 200 mm vs. 150 mm wafers. In addition, wafer planarity should not be worse in the 200 mm wafers. Due to the large fab/foundry overheads, and assuming 200 mm tools are in place, the cost of processing a wafer is to a first approximation unrelated to its size. So processing a 200mm wafer will produce about 1.8 times more devices than a 150 mm wafer at the same processing cost. Of course, a 200 mm wafer will be more expensive than a 150mm wafer, and that needs to be factored into the overall cost equation. Many silicon fabs/foundries are starting to process SiC wafers as well, and given the plethora of 200 mm Si fabs/foundries with fully depreciated tools, there are many large 200 mm Si companies waiting on the sidelines to enter SiC production when 200 mm wafers become commercially available. These are companies that have established 200 mm silicon wafer production and do not want to retool to fabricate at the 150 mm SiC wafer size that is currently commercially available. Therefore, when 200 mm wafers become available, many 200 mm fabs/foundries will start producing SiC devices. To illustrate the economic benefits of moving to larger wafer size, let us assume starting material cost parity per cm^2 between 150 mm and 200 mm wafers. Further assuming a \$1500 cost for a fully processed 150 mm SiC wafer, and 60% of that coming from the starting wafer material (40% fabrication cost), a back of the envelope calculation points to a 17% device cost

SiC Device Fabrication



SEM image showing the surface of SiC. The surface appears relatively smooth with some small, dark, circular features. The text "SiC surface" is overlaid in yellow at the bottom left.



The high value of the SiC/metal barrier results in rectifying metal contacts and post metal deposition anneal is required for ohmic contact formation. Typically, a 50-100 nm Ni layer is blanket deposited and patterned on the wafer for the simultaneous ohmic contact formation on the n-type and p-type doped regions, Fig. 4. Depending on the specifics of the fabrication process, isolating the

source from the gate areas with dielectrics can facilitate high yields in the subsequent high temperature processing.

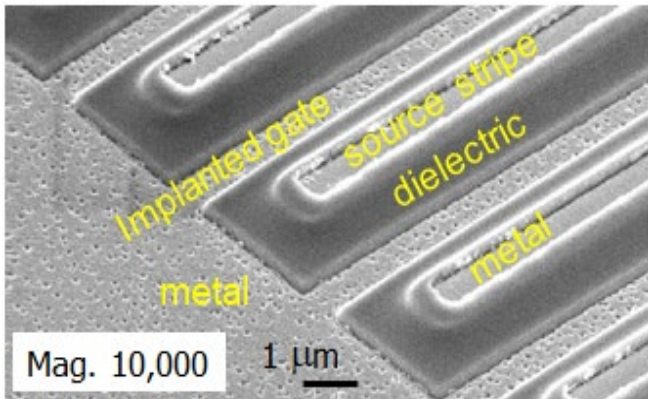


Fig. 4. Scanning electron microscopy image of a patterned Ni layer on a SiC wafer surface. Dielectric isolates the metalized p+ implanted gate areas (pitted surface) from the n-doped source stripes.

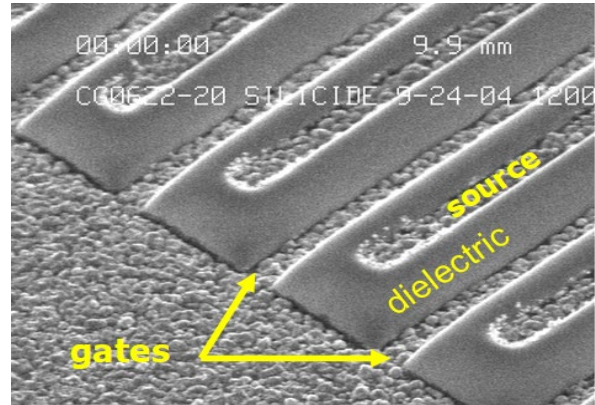


Fig. 5. Scanning electron microscopy image of the Ni patterned SiC wafer of Fig. 8, after a 950 °C rapid-thermal-annealing event. Ni silicide is formed with no shorting of the p-gate to the n-source regions.

High temperature annealing of the Ni patterned wafer creates Ni-silicide for low resistivity ohmic contact formation. Rapid thermal annealing (RTA) at 950 °C, using standard silicon fabrication equipment, was used to create Ni-silicide with no metal strings, Fig. 5. The dielectric isolates the source from the gate areas eliminating shorting during the high temperature silicide process.

Unlike Si wafers, SiC wafers are transparent. This complicates the use of “silicon” tools for CD-SEM and metrology measurements, as the focal plane is determined with the use of an optical microscope. SiC-specific wavelength metrology/inspection tools are now available from multiple vendors. Another issue is the relative lack of flatness of SiC wafers, compared to those of Si, which can complicate photolithography. In addition, the high-temperature SiC processing can further degrade wafer flatness, occasionally rendering wafers unusable. This is particularly problematic with the thick epitaxy wafers used in +3.3 kV device fabrication. Efforts are underway to produce flatter starting SiC wafers, and to minimize flatness degradation during fabrication. Lastly, the poor SiC/SiO₂ interface quality reduces inversion layer mobility. Thus, passivation techniques including annealing in nitrides are utilized to improve the SiC/SiO₂ interface quality similar to the case of silicon [4].

Device manufactures have developed IP for several SiC processing steps and compete on both design and processing. Although SiC is not fully CMOS-compatible, the SiC industry has leveraged Si technology processes and infrastructure by making the relatively small financial investments required to adapt existing fabs. Today, SiC manufacturing has matured and its fab infrastructure now mirrors that of Si. Integrated SiC device manufactures coexist with foundries and fabless companies, and design houses provide know-how and IP that can be leveraged to accelerate entry to market, Fig. 6. SiC device fabrication in volume fabs alongside Si has emerged as a “cost reduction” model exploiting “silicon” manufacturing economies of scale. Through re-purposing older fully depreciated 150 mm (and 200 mm in the near future) Si foundries, SiC power devices can be manufactured with the relatively small investments necessary to support the unique SiC processing steps. Minimizing fabrication cost by exploiting the mature Si volume production assumes the fab is loaded close to capacity with standard Si and SiC processes running on the same lines. In addition, aggregating the demand for SiC substrates and epilayers in volume fabs contributes to lower material costs. Lower fabrication costs in a fully depreciated Si+SiC “capacity loaded” fab, coupled with decreased material costs can lead to significant price reductions for SiC devices. This approach offers a new opportunity for outdated Si foundries, which have not kept up with the channel length reductions of the last two decades, to continue manufacturing legacy Si parts while ramping up SiC fabrication that requires relatively modest ~0.3 micron design rules [5].

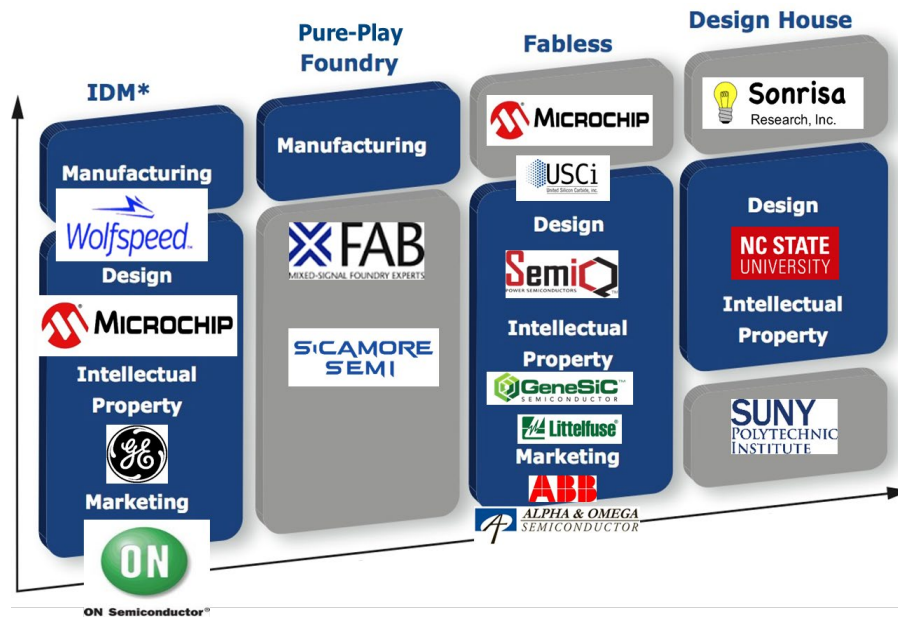


Fig. 6. The U.S. SiC fab infrastructure mirrors that of Si. It consists of Integrated Device Manufacturers, Foundries, Fabless companies, and Design houses.

Defects, Reliability, and Ruggedness

The majority of “killer” defects have been virtually eliminated in modern SiC wafers. Basal-Plane-Dislocations (BPDs) are the major remaining defect degrading device performance [6]. BPDs can propagate from the wafer substrate through the thickness of the epitaxial layers where devices are fabricated. BPDs can also be generated during the high-temperature ion-implantation fabrication process. In commercial wafers, more than 95% of substrate BPDs propagate as relatively “benign” threading edge dislocations in epitaxial layers grown off axis by CVD [7].

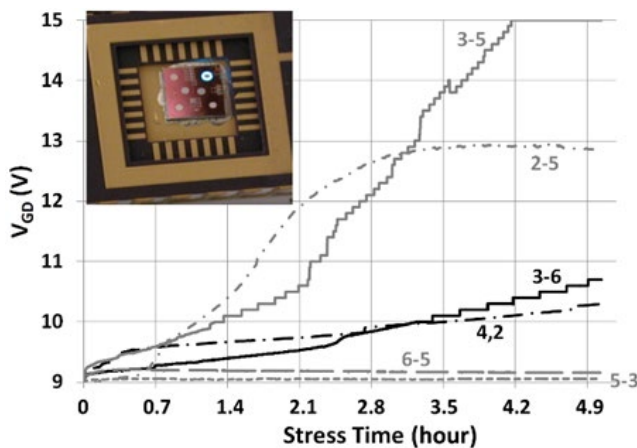


Fig. 7. Representative 100 μm drift layer SiC JFET forward gate–drain voltages as a function of time for a fixed dc 100-A/ cm^2 gate–drain bipolar stress. The compliance is set at $V_{\text{GD}} = 15$ V. A biased JFET, with its gate–drain diode’s bipolar current giving rise to blue/violet electroluminescence, is shown in the inset.

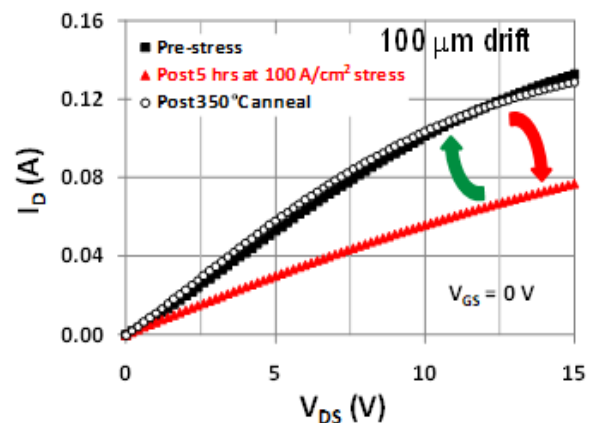


Fig. 8. BPD-related JFET ON-state conduction degradation and full recovery by annealing. The black squares, red triangles, and open circles represent the ON-state conduction characteristics prior to bipolar stress, after 5 hours of 100-A/ cm^2 bipolar stress, and after a 350 $^{\circ}\text{C}$ anneal, respectively.

When bipolar current flows through a SiC device, electron–hole pair recombination at BPDs in the drift layer provides the energy to activate dislocation glides that give rise to stacking faults and degradation. To investigate the impact of BPDs on the electrical characteristics of ion-implanted SiC transistors 17 JFETs with 100- μm drift epilayers (10 kV rated) were stressed at a fixed gate-drain DC

bipolar current density of 100 A/cm^2 for 5 hours. Representative curves are presented in Fig. 7 [8]. At 100 A/cm^2 , the gate–drain p-n junction is turned on, as evidenced by the emission of blue/violet electroluminescence at the edges of the JFET (inset photograph of Fig. 7), and bipolar current flows. Of the 17 JFETs stressed, six exhibit no forward gate-drain voltage degradation. This confirms that with optimized process flows and implantation recipes, BPDs are not generated during fabrication. Nine JFETs exhibit intermediate voltage degradation, and two exhibit severe voltage degradation. Bipolar current in the presence of BPDs leads to forward gate–drain p-n junction and ON-state conduction degradations as shown in Fig. 8. Interestingly, transistor BPD-related electrical degradations can be fully reversed by annealing at 350°C , while non-degraded characteristics remain unaffected by this annealing.

Threshold voltage instability is the main remaining reliability concern in SiC MOSFETs, which are the dominant transistors in SiC-based power electronics applications. It is primarily due to oxide traps at the SiC/gate-oxide interface. A positive shift in the SiC transistor's threshold voltage has the deleterious effect of increasing conduction losses, while a negative shift is undesirable as it can spontaneously turn the device on. Valuable SiC reliability data has been accumulated over years of field operation and is driving device optimization. SiC devices can be made more rugged by leveraging design trade-offs. This, combined with intelligent gate drives, can provide adequate circuit protection [9].

Summary

The compelling efficiency and system benefits of SiC are leading to wide adoption with insertion in electric vehicles being the volume application that enables manufacturing economies of scale and lower system costs. Industry is removing the last barriers to mass SiC commercialization that include higher than Si device cost, the presence of basal plane dislocations, and reliability and ruggedness concerns. The wafer represents a disproportionately high percentage of the overall SiC device cost, compared to that of Si, and technological improvements and transition to volume 200 mm wafer production will help lower those costs. SiC manufacturing has matured, non-CMOS compatible processes are fully developed, and the SiC fab infrastructure mirrors that of Si. Basal plane dislocations are the major remaining yield lowering defect to overcome. Gate-oxide interface quality improvements will enhance performance and alleviate any lingering reliability concerns.

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