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Silicon carbide as a material for mainstream electronics

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Abstract

SiC is emerging as the only semiconductor material other than silicon that can have electronically passivated surface to industrial standards. The surface passivation is the main reason for the dominance of silicon technology, but SiC has favorable bulk properties. This combination of factors raises the question whether SiC can play a role in mainstream electronics (integrated-circuit based complex systems). Addressing this question in this paper, it is concluded that SiC integration with silicon wafers is the most likely trigger of an evolutionary chain of investment and development steps, which has the potential to significantly influence future development of mainstream electronics.

Keywords: Silicon-carbide electronics; Surface passivation; Mainstream electronics; Low-leakage switches; Complex systems

1. Introduction

Electronics applications of silicon carbide have so far remained limited to power devices. The effort to develop silicon-carbide based power devices is justified because only diamond has, at least theoretically, a higher figure of merit for power devices. However, this focus of the silicon-carbide research on power electronics should not be a reason to ignore other potential applications. The properties of silicon carbide that make this material advantageous for devices used as power switches are also relevant for devices used as switches in digital circuits. The question then is whether silicon carbide can be utilized to enhance mainstream electronics applications.

To address this question in this paper, the key factors that determine the suitability of a material or device for mainstream applications are identified. This sets the context for analysis of the technical potential and the obstacles, both technical and commercial, related to suitability of silicon carbide for specific mainstream applications. The analysis identifies that integration of silicon carbide with silicon is the most promising technological approach.

2. Mainstream electronics: integrated-circuit based complex systems

The mainstream electronics, as is known today, has evolved over the last four to five decades through developments based on silicon technology. A number of other semiconductors have better bulk properties than silicon, yet their role remains limited to what is described as niche markets. The incredible development success of silicon technology would not have occurred if the development was limited to a competition with the old technology for the existing applications at the time (a competition with vacuum tubes for applications of signal amplifiers). Likewise, no remarkable development of SiC electronics should be expected if the development remains limited to a competition with Si for existing applications (either power electronics or digital circuits). As distinct from competing for applications of amplifiers, the dramatic development of silicon technology has been enabled by a long and continuous development of new applications. Importantly, a long chain of new applications cannot be created at the same level of sophistication or system complexity. The key factor

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that sustained the market for the incredibly long chain of new silicon applications has been the increasing level of sophistication of signal processing and transmission. This has been enabled by an increasing level of complexity of integrated electronic systems.

More complex systems integrate more switches and the leakage of each switch adds up so that the power consumption ultimately limits the complexity of a system achievable with a type of switch exhibiting a certain leakage level. Normally-off MOSFETs, in particular as complementary pairs in CMOS technology, provide low-leakage implementations of digital functions. Normally-off MOSFETs necessitate an electronically passivated semiconductor surface that was only possible to achieve by the Si–SiO_2 interface. Accordingly, all complex systems of the mainstream electronics are based on silicon.

The complexity increase of silicon-based integrated circuits cannot continue forever. As mentioned before, the ultimate boundary is drawn by the power-consumption limits. Many exotic nanosized structures could be developed on either silicon or on other materials, but that does not mean that they could be put together to perform a highly sophisticated function. The power-consumption limit is as fundamental as the second principle of thermodynamics. As distinct from this, there are no imminent market and application limits of increasingly complex information systems performing increasingly sophisticated functions. We are very far from the ideal information environment of being able to receive desired information instantly anywhere on the earth and beyond and to have means of distilling and presenting the information in the most suitable form for a consequent action in a specific situation.

3. Silicon-carbide potential: a unique semiconductor with passivated surface and wide energy gap

Silicon is no longer the only semiconductor with passivated surface to industrial standards. The current development of power MOSFETs demonstrate that the electronic passivation achieved by nitrided SiC–SiO_2 interfaces [1] is suitable for commercial applications. Moreover, it has been demonstrated that both surface and bulk leakage in SiC devices can be reduced to much lower levels that could ever be achieved by silicon [1]. The energy gap of silicon is relatively narrow, which means that either injection or generation of minority carriers leads to observable leakage current of any silicon-based switch biased in *off* mode. Therefore, it is silicon carbide that emerges as a unique semiconductor with electronically passivated surface and a wide energy gap, enabling low-leakage switches that cannot be achieved in silicon.

Potential applications of "leakageless" switches are many. A simple example is the possible implementation of the MOSFET switch from the 1C1T dynamic RAM (DRAM) cell in silicon carbide, which would turn this processing-type memory into a nonvolatile memory, therefore enabling the data-storage and data-processing functions to be performed by a single memory array. Importantly, it is the imminent technical and commercial challenges that will determine which application – if any – has a commercial chance. There are many technical challenges, but perhaps the most obvious one is the very high annealing temperatures needed to achieve selective doping by ion implantation. Because of this, the demonstrated MOSFETs on SiC are not self-aligned (the gate electrode is deposited after the doping and has to be aligned to the source/drain region). This is not a suitable structure for complex integrated circuits. However, technical challenges such as this are not insurmountable. The key question is whether a continuous evolutionary process consisting of investment steps and technical progress that ensures further investment could be achieved.

The current activities aimed at developing power and high-frequency devices on SiC, in particular MOSFETs as normally-off switches, could theoretically be the initial steps of such an evolutionary process. However, there is no likely chain of large enough niche markets to allow this process to evolve without a fatal competition from the mature silicon technology.

4. Integration of silicon carbide with silicon

The old saying, "if you cannot beat them, join them", seems applicable to this situation. Instead of full competition with silicon technology, there is an alternative option for SiC development: integration of SiC devices on silicon wafers. It is demonstrated that SiC films can be created on silicon wafers by epitaxial growth of 3C SiC [2–5] and by wafer bonding to create SiC-on-insulator structure [6]. Both these approaches would need considerable further development, and even if the industrial level of development could be achieved, the process would add complexity and cost to the standard silicon processing. The question then is whether the enhancements achieved by the added SiC layer could open application areas that would justify the increased cost. A good analogy here is the integration of bipolar and CMOS technology (BiCMOS): this integration does add complexity and a significant cost to the standard CMOS technology, but for some applications, it is commercially more viable approach than the obvious possibility of using off-chip bipolar components.

In comparison to BiCMOS, a mature technology that integrates SiC and Si does not need to use more additional masks (lithography levels) than what BiCMOS adds to the standard CMOS process. Therefore, the additional cost could become comparable to the additional cost for a BiCMOS process. As opposed to this, the technical opportunities opened up by integrating SiC devices with standard silicon electronics are much greater than the advantages of adding bipolar-junction transistors to the CMOS electronics. Importantly, this approach opens up the possibility to utilize any material advantage of SiC, not just the combination of passivated surface and wide energy gap ("leakageless" switches). These additional material advantages include the high breakdown field and thermal conductivity (for integration of power devices with silicon electronics – smart power devices), superior mechanical properties (for integration of MEMS devices with silicon electronics), absence of diffusion (for creation of nanoscale devices), different optical properties, etc.

5. Conclusions

The current status of SiC technology indicates that it is possible to develop *technically* superior SiC-based devices in comparison with the mainstream silicon-based technology. However, the gap between the current status with the development of power devices on SiC wafers and the development level that is needed for a successful competition with the state-of-the-art silicon technology is so large that it would need a very unlikely revolutionary-type of investment. Although somewhat neglected, the approach of SiC integration with silicon wafers could enable an evolutionary chain of investment and development steps because it utilizes the material advantages of SiC to enhance silicon-based applications with a justifiable cost increase.

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