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An Overview of SiC as the Nonvolatile Random−Access Memory Material

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Abstract

The extraordinary intrinsic properties of SiC have made this material a suitable choice to use in high temperature, high frequency, and high voltage applications. In additional to these, SiC could be employed as the based material for nonvolatile memory applications, mainly due to its extremely low thermal-generation rate at room temperature. In this paper, the reasons of using this material in this particular application is presented and the development of the application over the past fifteen years is reviewed.

Key Words : SiC, Nonvolatile, Random-Access-Memory(RAM)

1. Introduction

The demand for nonvolatile memory in the global market is increasing, mainly due to the growing number of portable, compact, and light-weigh electronic appliances [1]. Nonvolatile memory, having the ability to retain stored information for longer than 10 years at temperatures as high as 80°C even without power supplied, is the main requirement for a permanent or semi-permanent storage medium in the above-mentioned devices/systems.

The Si-based nonvolatile memories only associate with read-only-memory (ROM) technology. These devices, such as flash memory, can only withstand limited operation cycles, with too long charging/discharging times to allow their use for random-access memory (RAM) applications [1]. RAMs such as dynamic RAM (DRAM) use metal-oxide-semiconductor (MOS) or metal -insulator -metal capacitors as storage elements. They respond very quickly (nanoseconds) during charging/discharging cycles, but they are volatile and need refreshing in order to maintain the stored data. This is a disadvantage for the above-mentioned gadgets. As a result, many researchers are motivated to find ways and means to develop a next generation nonvolatile memory. SiC has superb intrinsic properties [2], [3] and able to fabricate acceptable quality of MOS capacitors on it [4], theoretically enabling *nonvolatile random-access memory* (NVRAM) memory elements with access characteristics of Si RAMs and with retention characteristics of Si ROMs to be made. Although this great concept has been known back in 90s, the development of this type of device is relatively slow and SiC research community has less interest in this application compared to the others, such as power devices and applications. The aim of this paper is to review the development of SiC as the based material in nonvolatile-memory device, over the past fifteen years, and to introduce the advantages of this material for this special application.

2. Investigation and discussion

2.1 The Advantages of SiC as Nonvolatile Random-Access Memory Material

SiC exhibits unique material properties, having four promising features to enable it to consider as the next generation nonvolatile-memory material, namely (1) large bandgap with extremely low intrinsic-carrier concentration, *n*i, (2) ability to withstand harsh environment, such as at high temperature, (3) ability to thermally grow native oxide (SiO_2) on SiC as dielectric, and (4) the developed planar technology in Si can be used with little modification in SiC.

Since there are numerous polytypes of SiC, the overview of the advantages of SiC as nonvolatile random-access memory substrate is only focused on the most popular and most widely reported polytypes. They are 3C, 4H, and 6H SiC. The bandgaps of these polytypes are 2 to 3 times larger than the Si (1.12 eV) [2]. The larger the bandgap is, the lower the *n*i should be. For example, *n*i for 4H SiC is in the order of 10-7 cm-3at room temperature. It is approximately 17 orders of magnitude lower than in Si. Given that the rate of thermal generation of minority carriers is proportional to *n*i, the thermal generation rate in 4H SiC should be 17 orders of magnitude longer than in Si. Theoretically, the thermal generation rate at room temperature is negligible. Thus, the unintentional change of logical states due to thermal-generation process should be insignificant in a SiC-based memory device.

The applicability of SiC for harsh environment applications, such as high temperature, has long been recognized. Recently, Li *et al.* [6] reported a Flash-Memory-like structure on 6H SiC as a nonvolatile memory that is able to withstand temperatures as high as 200°C.

The remaining two features are related to device-fabrication technology. It is possible to grow thermally stable SiO_2 layer on SiC with the commercially available equipment from standard Si planar technology. Unlike other wide-bandgap materials, SiC is the only material that can oxidize thermally to form SiO_2. Oxidation technology seems to play a major role in determining the quality of the SiC-SiO_2 interface and subsequently affecting the charge-retention time of a memory device [7].

2.2 The Development of SiC-based Nonvolatile Memories

Fifteen years ago, researchers from Purdue University have successfully developed and patented the first SiC bipolar-based nonvolatile memory [8][11], which consisted of a bipolar transistor as a switch to control charges and a *pn*-junction diode as a storage element. In this *npn* structure on 6H SiC, Gardner *et al.* [8] reported charge-retention time at room temperature of $\sim 3x10^6$ years. In that study, the length of charge-retention time was improved to $\sim 10^6$ s by using dry SiO_2 as terminal-junction passivation layer compared to using wet oxidized passivation layer. The authors concluded that the effect of surface passivation at the surrounding devices plays a major role. Using the same structure but fabricated on 4H SiC, charge-retention time in the range of 21-43 years is reported [9]. In comparison, the charge-retention time for device fabricated from 4H SiC is shorter than from 6H SiC. Wang *et al.*[9] have attributed this effect to the quality of substrate or/and epilayer. There are a few disadvantages using bipolar structure as storage elements, namely, low packing density [5] and high power consumption, approximately 2-3 times more power is consumed in a bipolar structure than in a MOS structure [5].

Based on the studies in Si, the problems in bipolar structure as nonvolatile memory can be solved using MOS capacitor, such as in the structure of a Si-based one-transistor one-capacitor (1T1C) DRAM. In the case of MOS capacitor as storage element, the charge is stored in a potential well created by surface-band bending due to applied gate voltage. Cooper *et al.* and Agarwal *et al.*[10] reported this conceptual idea, however, this idea did not support by any experimental result. This is because the measurements of non-equilibrium charge characteristics in SiC-based MOS capacitors are impossible at that time. The main reason behind this is probably because of difficulty to find a right process to obtain an acceptable quality of SiC-SiO$_2$ interface that prevents the charges leak through the oxide. Recently, high-quality SiC-SiO$_2$ interface, with acceptable level of SiC-SiO$_2$ interface-trap density was reported using nitridation process [4], [9]. Utilizing this process to grow gate oxide, the nonvolatile-memory characteristics of MOS capacitor on SiC are achievable and are reported for the first time [3], [11]-[16]. The proposed nonvolatile-memory device is having a similar structure and operation mechanisms to the Si-based 1T1C DRAM. Given that the volatile characteristics of Si-based DRAMs are due to several severe leakage paths, the identification and examination of these leakage mechanisms in a SiC-based 1T1C NVRAM is necessary. The possible leakage mechanisms, causing unintentionally change of logical states in the memory, consist of six different paths. They are [16]: (1) leakage through the dielectric of the storage MOS capacitor, (2) electron-hole generationin the depleted region of the storage MOS capacitor, (3) junction leakage due to electron-hole generation in the depletion layer surrounding the drain region of the select MOSFET, (4) leakage through the select MOSFET due to its subthreshold current, (5) tunneling current through the gate dielectric of the select MOSFET, and (6) band-to-band tunneling at the edge of the select MOSFET.

The potential of developing a 1T1C NVRAM on 3C, 4H, and 6H SiC has been experimentally investigated [3], [11]-[16]. From literatures, the investigations were only concentrated on three possible leakage paths [(1) to (3)]. There is no report on the remaining leakage paths. MOS capacitors fabricated on SiC with nitrided oxidesemiconductor interfaces [17] were used in the investigations, either as memory elements themselves or as test structures to determine the junction leakage in select MOSFETs, which is connected to the memory elements. Charge leakage through gate oxide has been identified as a main technological issue for the development of the memory elements. Using nitrided SiC-SiO$_2$ interface, this problem can be minimized. Leakages due to electron-hole generation in depletion regions of both the MOS capacitor and of the reverse-biased *pn* junction surrounding the drain region of a select MOSFET, do not have significant effect on the nonvolatile characteristics of the proposed device. Table 1 summarizes the relaxation times of the three possible leakage paths [3], [11]-[16].

TABLE 1: Estimated room-temperature relaxation times deduced from different leakage paths.

Leakage path	Relaxation time, τ (s)	
	N-type 4H-SiC	P-type 4H-SiC
1	8×10^{12}	3×10^{12}
2	1×10^{17}	1×10^{16}
3	1×10^{19}	2×10^{18}

: a positive voltage is applied to the surrounding of the capacitors (MOS capacitor with shielding ring) [12]. *2*: measured by floating-gate technique [15]. *3*: mathematical analysis introduced in Ref. [16].

3. Conclusion

The advantages of SiC as nonvolatile memory material and the development of this material in this particular application havebeen systematically reviewed. From the scare knowledge accumulated so far, the leakage path via the capacitor oxide remains a crucial factor for the development of the device. Besides, the quality, the size, and the cost of substrate and epitaxial layer are also important factors to determine the successful use of this material in nonvolatile-memory applications.

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