Comparison between GaN and SiC for power switching transistor application

Haoxiang Yu
Material science and engineering, University of California, Davis, California, 95618, USA
Corresponding E-mail: angela@cas-harbour.org

Abstract. Semiconductor has been widely used in industry ever since its invention and has experienced three generations. However, there are still many problems existing in the third generation semiconductors industry such as making process and cost. This paper mainly discusses the differences between GaN and SiC in material properties and fabrication process. Material properties include band-gap, critical field strength, carrier mobility, and thermal conductivity. For fabrication process, GaN is normally used homoepitaxy approach and SiC is used heteroepitaxy approach. The details in these two approaches are given in the paper.

1. Introduction
Semiconductor has been widely used in industry ever since its invention and has experienced three generations. Each of these generations bring a great progress to our electronic devices. From silicon and germanium to semiconductors compounds such as GaN and SiC, electronic devices involved semiconductors are becoming smaller but more advanced. With the advent of third generation semiconductors which are composed of compounds whose band gap is larger than 2.3eV, third generation semiconductors have emerged and show great advantages in high power and high switching frequency devices such as lasers and detectors. Compared with the first and the second-generation, the third-generation materials have outstanding features in higher breakdown electric field and thermal conductivity. Therefore, they are more suitable to work in high power device under high temperature and high radiation condition.

Although the introduction of third generation semiconductor allowed us to break through the limitation and obtained higher performance device, it’s not as widely applicable as first and second generation semiconductors in industry. There are still many problems existing in the third generation semiconductors industry such as making process and cost. Many conflicts in making process reduced the stability of the device and increased cost. Thus it’s impractical to extensive production with a great cost. However, in some specific areas, such as aerospace, third generation semiconductors play an important role. In our daily life, the combination of first and second generation semiconductors can complement shortcomings of each other and reduced cost. More properties and applications of third generation semiconductors are still developed.

In this paper, GaN and SiC, which are two representatives of third generation semiconductors, are mainly discussed in comparison between their material properties and structures. This paper serves to differentiate these two semiconductors’ function and provides some problems exiting in MOSFET making in order to give readers better understanding of these two materials.
2. Comparison in Material properties
There are four important material properties related to semiconductor, including band-gap, critical field strength, carrier mobility, and thermal conductivity. These four properties determine the performance of the devices [1].

2.1. Band gap
Band gap is the energy difference between valence band and conduction band. In general, it is the minimum energy that is required to excite an electron from valence band to conduction band. Only electrons in conduction band can conduct electricity. For semiconductors, their band gap is normally less than 5eV. In table 1, it shows that band gap of SiC is almost same as GaN’s. Electrons in GaN and SiC require almost same energy to jump from valence band to conduction band. If band gap is the only consideration, both two materials should operate at high temperature and high voltage conditions [6].

2.2. Critical field
In semiconductor, critical field is also called breakdown field. This parameter indicates the minimum voltage the material become electrically conductive. Breakdown field depends on band gap. In the field, electrons accelerate to a very high velocity and create an electron-hole pair. These created pairs can accelerate themselves and create more pairs. Therefore, this process would produce an avalanche of particles. The equation between band gap and velocity of electrons is given:

\[ \frac{1}{2}mv^2 = E_g \]

where \( m \) is the mass of electrons, \( v \) is velocity of electrons, \( E_g \) is the band gap energy. With similar band gap energy between GaN and SiC, their critical field is close. But SiC’s is slightly higher. With same length of material, SiC has a higher breakdown voltage.

2.3. Electron mobility
Electron mobility indicates how quickly the electron can move through the semiconductor. Electron mobility can influence the material in two aspects. First aspect is the conductivity of material. Conductivity is proportional to the product of electron mobility and carrier concentration.

\[ \sigma = e(n\mu_e + p\mu_h) \]

where \( \sigma \) is conductivity, \( e \) is electron charge, \( n \) and \( p \) are concentration of electrons and holes [5], \( \mu_e \) is mobility of electrons, and \( \mu_h \) are mobility of holes. In table 1, GaN’s electron mobility is much higher than SiC’s. This means the conductivity of GaN is much better than SiC. This characteristic help GaN device have much less energy lost. Second aspect is influencing frequency response. This influences include two ways. First, the carrier velocity is proportional to the mobility in low electric fields. Therefore, higher mobility corresponds to higher frequency because carriers take less time to go through the device. Second, under same condition higher mobility means higher current. Higher current can charge capacitance more quickly. Hence, it results in higher frequency response. GaN with high carrier mobility indicates that it is a better option for high frequencies device.

2.4. Thermal conductivity
Thermal conductivity refers to the ability of material to conduct heat. In making device, it is an important factor because it defines the limitation of the material. In semiconductor devices, high thermal conductivity means the material needs less help from external environment to dissipate the heat. In most circuits, the resistance in each components generates a lot of heats. With good thermal conductivity, the material can work at higher temperature and higher power. In Table 1, SiC’s thermal conductivity almost 4 times higher than GaN’s. This gives SiC device a great advantage in the real application.

In summary, for SiC transistor and GaN transistor, the material properties we are interested are band-gap, critical field strength, carrier mobility, and thermal conductivity. High critical field of both SiC and GaN allows them to work at a higher voltages and lower leakage currents. High electron mobility allows them to work in high frequency of operation. Meanwhile, GaN and SiC have different advantages in
these properties. GaN is more suitable for high frequency device due to its higher electron mobility, while SiC, has higher thermal conductivity thus having advantages in operating higher power.

Table 1. Material Properties of Si, SiC and GaN

| Material property          | Si    | 4H-SiC | GaN  |
|---------------------------|-------|--------|------|
| Bandgap (eV)              | 1.12  | 3.26   | 3.4  |
| Critical field (V/cm)     | 0.3   | 3.5    | 3.3  |
| Carrier mobility (cm²/V × sec) | 1500 | 650   | 990, 2000* |
| Electron saturation velocity (cm/sec) | 10  | 20    | 25   |
| Thermal conductivity (W/cm² × K) | 1.5 | 5     | 1.3  |

*In bulk GaN/2D electron gas region of GaN/AlGaN HEMT, respectively.

3. Comparison in SiC and GaN MOSFET structure

MOSFET structures for SiC and GaN are very different. As showed in figure 2, in power switching applications, transistor requires an epitaxial layer of either SiC or GaN, which is going to grow or deposit on a substrate that either the same material as the epitaxial layer (homoeptaxy) or a different one (heteroeptaxy).

For SiC, homoepitaxial approach is the best approach. The most commonly used epitaxial technique for growth of SiC is chemical vapor deposition[2]. It is a process in which gaseous compounds transfer to the substrate surface resulting information and growth of the desired material. The temperature for 6H-SiC layer growing on 6H-SiC substrate by CVD is range from 1500-1850°C. One way to lower the temperature and stabilize the material is to disorient substrate by a few degrees off {0001} in the <112̅0> direction. This growth is so-called step-controlled epitaxy and it can make the poly-type structure more stable. The result turned to be successful in conducting ability from top to bottom of the wafer.

For GaN, although homoeptaxy approach has advantages over the heteroeptaxy approach that has less defects on the material, today’s technology can’t produce high quality (low defect) GaN substrates with homoeptaxy approach. So most devices made of GaN are produced by heteroeptaxy approach, which is a GaN epi on SiC, Si, and sapphire substrate [3]. The most widely used method to produce heteroeptaxital GaN bulk is HVPE (hybrid vapor phase epitaxy). It can reach high growth rates (<300 um/h), control of impurities, high volume output, high purity substances and large wafer size. However, there are also many disadvantages in HVPE method[4]. Under high strain condition, GaN substrates are easily bowing and cracking at the interface of GaN and non-native substrate materials because of their different thermal expansion coefficients. However, there are some new researches that reduced some
limitations caused by bowing and cracking in GaN on Si substrate and GaN on sapphire substrate. The GaN bulk creating with HVPE process has dislocation densities lower than $10^6 \text{cm}^{-2}$.

4. Comparison in cost for making SiC device and GaN device
Cost is another important factor when designers made their choices. In general, GaN MOSFET requires more money than SiC MOSFET, because GaN MOSFET needs a buffer layer to accommodate differences in crystallography. An extra buffer layer not only increase the production cost but also creates plenty of defects between non-native substrates. Manufacturers also need to improve and spend more money on dealing with these defects. Thus building GaN devices, more money is required to overcome these problems in order to keep devices operate normally. So in general, GaN MOSFET cost 20% more than SiC MOSFET. Because SiC doesn’t have problem with matching substrate and epitaxial layer, the power efficiency can increased about 20 percent.

5. Suggestion
From comparison in material properties, MOSFET structure and cost, it’s obvious that SiC have advantages in thermal conductivity and cost and GaN has advantages in electron mobility. And these two semiconductors also have many aspects in common such as band gap and critical field. Therefore, I suggest choosing SiC when both materials can satisfy requirements or device are needed to operate at high temperature environment. With same amount of material, cost of SiC can save up to 20%. These savings can be used to improve other aspects of the device. But GaN is still very important when devices are required high frequency switching especially in computers. That’s why scientists are still working on developing homoepitaxial approach for GaN. In GaN made devices, manufacturers need to pay more attention on heat radiation.

6. Conclusion
Both GaN and SiC are important semiconductors in the industry. The technology of producing SiC is relatively more mature than that of GaN. However, GaN has many advantages over SiC in various aspects. A brief comparison of GaN and SiC in material property and their fabrication method is the main focus of this paper. For material properties, there are differences in band-gap, critical field strength, carrier mobility, and thermal conductivity between GaN and SiC. For fabrication process, homoepitaxy approach is normally used for SiC while heteroepitaxy approach is widely used for GaN.

Reference
[1] Flack, T. J., Pushpakaran, B. N., & Bayne, S. B. (2016). GaN Technology for Power Electronic Applications: A Review. Journal of Electronic Materials, 45(6): 2673–2682. doi: 10.1007/s11664-016-4435-3
[2] Park, Y. S. (1998). SiC materials and devices. San Diego: Acad. Press.
[3] Aida, H., Takeda, H., Aota, N., and Koyama, K. (2012). Reduction of Bowing in GaN-on-Sapphire and GaN-on-Silicon Substrates by Stress Implantation by Internally Focused Laser Processing. Japanese Journal of Applied Physics, 51(1R): 016504. doi: 10.7567/jjap.51.016504
[4] Aida, H., Koyama, K., Martin, Ikejiri, K., Aoyagi, T., Takeuchi, M., etc. (2013). Growth of Thick GaN Layers by Hydride Vapor Phase Epitaxy on Sapphire Substrate with Internally Focused Laser Processing. Applied Physics Express, 6(3): 035502. doi: 10.7567/apex.6.035502
[5] Ramsden, E. (2011). Hall-Effect Sensors: Theory and Application. Newnes.
[6] A.A Burk Kr., Mj O’Loughlin, R.R Siergiej, A.K Agarwal, S. Sriram, R.C Clarke, M.F MacMillan, V Balakrishna, C.D Brandt (1999) SiC and GaN wide bandgap semiconductor materials and devices, 43(8): 1459-1464.