Power-switching beyond silicon: features of GaN devices

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Abstract. The generation, transmission, and use of electric power require different forms of power conversion. The commonly used electronic circuits for power conversion utilize switching techniques and, consequently, are referred to as switch-mode power electronic circuits. Two types of semiconductor-based switches are widely used in these circuits: two-terminal rectifiers (diodes) and three-terminal controlled switches (transistors). Currently, many integrated circuit devices use Silicon as the main substrate, because silicon is easy to purify and crystallize. Moreover, it is cheaper than nearly most of other semiconductor material. Silicon becomes main semiconductor material in today’s developments of power-switching. However, silicon’s energy gap is not large enough, which is the limitation of realizing more functions. With the requirement of new material to break the boundary of material limitation, the third-generation semiconductor rise up. This article will discuss the ideal requirements of power switching and how these requirements were realized by GaN through the method of deriving equations. Meanwhile, comparing with advantages of GaN, this paper will point out the silicon’s shortages. Finally, discussing reasons why GaN did not substitute Si then become the main semiconductor material among diodes or transistors.

1. Introduction
Many scholars have done researches to explore the excellent qualities of GaN. Comparing to Silicon, the main semiconductor material nowadays, GaN is particularly suitable for integrated circuit devices, especially for power conversion. Generally speaking, a good kind of power conversion ought to have high-blocking voltage, high-power efficiency and high-switching speed. However, people do not put two materials together to compare materials’ properties and analyzing why GaN is better than Silicon as a semiconductor material. Based on the purpose above, this essay will compare GaN and Silicon as a power switching material in three points: the blocking voltage, the power efficiency, and the switching speed. By comparing GaN power switching with Si power switching, people will know the reasons why GaN is better than Si as a material of power switching clearly.

2. Blocking voltage of GaN devices
The dielectric will lose its dielectric properties and become a conductor under the action of a strong enough electric field, which is called dielectric breakdown, and the corresponding voltage is called breakdown voltage. But for a switch, blocking voltage can be applied on the switch that is OFF mode, which is reverse-bias voltage. Blocking voltage need to interact with the atomic bonds. Nevertheless, blocking voltage relates to the strength of atomic bonds. The value of breakdown voltage also corresponds to planer’s structures and to the semiconductor region’s doping concentration. This region is drift region for GaN. But how do we get the blocking voltage for a planer structure?

According to one-dimensional Poisson equation
\[ V_B = \frac{\varepsilon_s E_{Cr}^2}{2qN_D} \] (1)

We can obtain breakdown voltage for a planar structure. In Equation 1, \( V_B \) is the breakdown voltage, \( E_{Cr} \) is the critical or breakdown electric field, which is related to the energy gap of the material. \( N_D \) is the \( n \)-type doping level, \( \varepsilon_s \) is the semiconductor permittivity, and \( q \) is the value of electron charge. For a specific material, \( E_{Cr} \) and \( \varepsilon_s \) are constants. Obviously, \( q \) is constant (\( q = 1.6 \times 10^{-19} C \)) also. So that if we want to get the maximum of \( V_B \), we need to make \( N_D \) as small as it can.

The breakdown electric field of Si is around \( E_{Cr} = 30 V/\mu m \). And the semiconductor permittivity of Si is about \( \varepsilon_s = 11.8 \times 8.85 \times 10^{-12} F / m \). Assuming the doping level \( N_D = 5 \times 10^{14} cm^{-3} \). The breakdown voltage is 600V.

As we have discussed, blocking voltage relates to the strength of atomic bonds, which can be indicated by the value of energy gap. The energy gap in Si is 1.12eV. However, the energy gap in GaN is 3.39eV, which means that \( E_{Cr} \) of GaN is higher than Si. \( E_{Cr} \) for GaN equals around 300V/\( \mu m \), which is ten times bigger than \( E_{Cr} \) of Si. The semiconductor permittivity for GaN is \( \varepsilon_s = 10 \times 8.85 \times 10^{-12} F / m \). At the same doping level with Si \( (N_D = 5 \times 10^{14} cm^{-3}) \). The blocking voltage of GaN is closer to 50,000V. From the results we can observe the huge gap between the two.

In the field of engineering applications, how do we get the maximum of breakdown voltage when the electric field is a specific value for GaN. According to (1) equation, \( \varepsilon_s \) is constant. \( q \) is constant \( (q = 1.6 \times 10^{-19} C) \) too. The smaller the \( N_D \) becomes, the bigger the breakdown voltage is.

### 3. Power Efficiency of GaN devices

The best efficiency of energy conversion, of course, is as close to 100 percent as possible. Due to the exist of resistance and current, parts of energy converts into heat then disperse into atmosphere. So, if we want to improve the efficiency of energy conversion, the first thing is to reduce the ratio of energy conversion to heat energy.

Energy losses can be classified into static and dynamic. Dynamic energy losses mean energy losses during charge and discharge of capacitors. The equation of dynamic energy losses is below.

\[ P_d = f CV_C^2 \] (2)

In this equation, \( f \) means the switching frequency. \( C \) is the value of capacity and \( V_C \) is the voltage of stray capacitance.

The static energy losses are decided by the voltage when switches are in on mode.

\[ P_s = IV \] (3)

According to the equation, the bigger voltage is, the more power converted into heat. In the case of both diodes and transistors, the main source of static power losses is the resistance of the low doped drift region, which is necessary for achieving high-blocking voltages.
Figure 1. The role of the drift region in power rectifiers/switches and the relationship between the specific ON resistance and the maximum achievable breakdown voltage.

Defining specific ON resistance of the drift region as the ON resistance for a given area

\[ R_{SP} = \rho L_N = \frac{L_N}{q\mu_n N_D} \]  

(4)

As can be seen, the length of the drift region (\( L_N \)) should not be smaller than the width of the depletion layer (\( w_d \)) when the maximum reverse bias voltage, which is the breakdown voltage, is applied:

\[ L_N \approx \frac{W_d}{2} = \sqrt{\frac{2\varepsilon_s V_B}{N_D q}} \]  

(5)

In the diodes or transistors, the main resistance is the resistance of drift region (on mode). According to the equation below.

\[ R_{SP} = \frac{W_d^2}{\varepsilon_s \mu_n E_{CR}} \]  

(6)

\( V_B \) is breakdown voltage. \( \varepsilon_s \) is semiconductor permittivity. \( E_{CR} \) is the breakdown electric field.
The relationship between the maximum blocking voltage and the ON resistance is illustrated in figure 1.

![Figure 1. The relationship between the maximum blocking voltage and the ON resistance.](image)

**Figure 1.** The relationship between the maximum blocking voltage and the ON resistance.

Assuming that 20A of current have to be conducted by switch. The active area of device is 1 $cm^2$. For specific resistance of 0.1 $\Omega \cdot cm^2$, which corresponds to the breakdown voltage 1000V of GaN and corresponds to the breakdown voltage around 20V of Si. $R_{sp}$ equals to 0.1 $\Omega$. Voltage quals to 2V, which below the breakdown voltage of GaN and the breakdown voltage of Si. And power loss is 40W. This analysis shows that the breakdown electric field limits the practical blocking voltages that can be achieved by GaN devices to values below 1000 V.

**4. Switching speed of GaN devices**

If a power switching device has a high-switching speed, this device will be widely used in integrate circuit, which avoids long switching delays. Meanwhile, comparing to the normal switch, the size of power switching device is much smaller. Therefore, many spaces in the chip are available. As we all known, spaces in chip are most important. By using these spaces, we can make chip become more and more small. Electric devices can be designed smaller and smaller. The size of a chip means the development of technology.

For using gallium nitride devices, power manufacturers can get the faster switching components. Most inefficiency of power conversion the result of switching losses. So that gallium nitride (GaN) devices have more efficiency advantages than slow MOSFET switching elements. Moreover, Faster switching speeds greatly reduce magnet and the size of capacitive circuit elements.

**5. The potential of GaN**

GaN is another wide energy gap material with a very high breakdown field which makes it attractive...
for the development of power switches. GaN is usually grown on other substrates, most frequently on sapphire but also on SiC wafers. When grown on SiC wafers, the combined material is more expensive than just SiC, and it exhibits a much higher density of defects than SiC. Because of the higher defect density in comparison to SiC and a higher cost in comparison to GaN grown on other substrates, GaN grown on SiC is not used for power electronic devices; its use is for fabrication of blue (and consequently white) light emitting diodes that utilize the wide and direct energy gap of GaN. The very high density of defects does not cause fatal short circuits and recombination centers that would inhibit the light-emitting operation. Encouraged by the fact that these defects are not fatal, power transistors for microwave applications have been developed and commercialized with GaN grown on Si substrates. Although the defect density in this material is even higher than that for GaN grown on sapphire, the cost of this material is significantly reduced by the cheaper Si substrate.

Commercial power transistors using GaN are based on the HEMT structure. One disadvantage of the HEMT structure is that the current flow is lateral, and the power devices require both the source and drain contacts to be created at the surface. This results in less efficient utilization of the surface area in comparison to the vertical MOSFETs using SiC; however, the loss is smaller than the area gain that can be achieved by 100 times more electron mobility. The most important disadvantage of the HEMT structure is that the 2DEG is created by the polarization charge, which means the HEMTs are ON for zero gate voltage—a normally ON device. To turn the switch OFF, a negative gate voltage is applied. This feature appears to be an advantage when HEMTs are used as amplifiers for microwave applications. However, this is a undesirable feature, when HEMTs are used as power switches (the fourth key requirement for a power switch is the normally OFF operation). To resolve this problem, commercial GaN HEMTs are connected with a Si MOSFET in the configuration, which is typically referred to being as a cascode connection. As it can be seen, the Si MOSFET provides the normally OFF operation, whereas the GaN HEMTs provide high-blocking voltage and low ON resistance. The ON resistance of the Si MOSFET is added to the ON resistance of the HEMT; however, the Si MOSFET is a low-voltage device with a small ON resistance because it does not require a drift region.

![Figure 3. Cascode connection between a Si metal oxide semiconductor field-effect transistor.](image-url)

The cascode connection between a Si MOSFET and GaN HEMT enables the advantages of GaN HEMTs to be practically utilized; however, it is not the ideal solution. With this potential to significantly reduce the cost of power switches created in GaN, it becomes very attractive to work on the problem of normally OFF conduction and to create a normally OFF HEMT. Many research
activities are guided by this insight. Some of the approaches have included the use of a gate material with a larger work function, while others have focused on introducing negative charge in the gate area, and yet another approach is to deposit a $p$-type doped GaN or AlGaN layer on top of the AlGaN barrier. A gate dielectric between the gate metal and the AlGaN film is used to reduce the gate leakage. The structure created by utilizing a gate dielectric is usually referred to as a MOS-HEMT. If this effort is successful and a normally OFF HEMT or MOS-HEMT is developed, it has the potential to become the dominant device because of the significant power dissipation and cost advantages.

6. Discussion
There are many applications in our live, which use many kinds of semiconductor devices. For instance, many electrical appliances in our life need to consume AC power. But if we obtain energy from solar cells, which is in the form of DC. Therefore, we need to convert DC power from solar cells to AC power that many appliances can use. Meanwhile, before AC power flood into DC circuit, AC-to-DC conversion is also needed. If we need low DC power, but we have high DC power. We need DC-to-DC conversion to convert high power into low power. Indeed AC-to-AC conversion is also needed. Converging high AC power into low AC power, or low AC power into high AC power. Which devices can be used is determined by which kind of power we need. Based on the comparison I mentioned above, people might have question why GaN do not widely used nowadays?

The semiconductor device made of Si material has good resistance to not too high temperature and radiation. Because of the abundant storage of Si, silicon has become the most widely used semiconductor material. Actually, GaN has quality that limited widely use. Growing gallium nitride films on silicon carbide or sapphire substrates by heteroepitaxy is the main method of using GaN. The lattice matches between GaN and SiC is well, failure rate was only 3.5%. But SiC is expensive. So that SiC cannot be widely used. Saphhire and gallium nitride have a lattice mismatch of 14 %. And sapphire is also cheaper than SiC. But sapphire has high hardness, brittleness, high resistivity, and a much higher price than silicon. Si is cheap. however, the lattice mismatch between the GaN and Si is as high as 17 percent. Therefore, much research is needed to reduce epitaxial defects by using transition layers. Moreover, for a long time, the p-type effective doping concentration of GaN materials is not high, so it is impossible to realize p-type heavy doping. Currently, improving the technological level and finding ways to eliminate the barriers can make GaN devices more widely used than Si devices.

7. Conclusion
Through the comparations that are mentioned above, we can clearly know the advantages of GaN as a semiconductor material. However, these comparations just among aspects of properties. In order to realize the widely use of GaN as a material of power switching, we need to consider the price, the qualities of combination with other semiconductor materials and nature storage. Basically, if these obstacles are conquered, GaN will substitute Si soon. Silicon, now we used as main semiconductor material, have abandon sources and well combination qualities with most materials. More explorations are needed for GaN to improve its properties. In my reference, the alloy of GaN and other material might have surprise qualities. GaN is not as plenty as Si, what if the combination of Si and GaN. The combination might have unique properties. They may have complementation.

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