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Silicon—a new substrate for GaN growth

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Abstract. Generally, GaN-based devices are grown on silicon carbide or sapphire substrates. But these substrates are costly and insulating in nature and also are not available in large diameter. Silicon can meet the requirements for a low cost and conducting substrate and will enable integration of optoelectronic or high power electronic devices with Si based electronics. But the main problem that hinders the rapid development of GaN devices based on silicon is the thermal mismatch of GaN and Si, which generates cracks. In 1998, the first MBE grown GaN based LED on Si was made and now the quality of material grown on silicon is comparable to that on sapphire substrate. It is only a question of time before Si based GaN devices appear on the market. This article is a review of the latest developments in GaN based devices on silicon.

Keywords. GaN; MOCVD; epitaxial growth; devices.

1. Introduction

Silicon substrates are low cost, available in large diameters and have well characterized electrical and thermal properties. Despite these advantages silicon has not been popular as a substrate material for GaN growth due to several problems mainly related to the cracking of GaN film due to stress. These stresses are not so high in magnitude for sapphire or SiC substrates. In 1971, group III nitrides (AlN) were grown on silicon by MOVPE (Manasevit *et al* 1971). However, research activity in group III nitrides remained stagnant over the next two decades until progress in GaN growth on sapphire by low temperature seed or buffer layer (Amano *et al* 1988) as well as the development of *p*-type doping technique (Amano *et al* 1989; Nakamura *et al* 1992) took place. Much of this phase of research centred around growth on sapphire and SiC.

Silicon attracted attention as a substrate material for GaN growth when the first MBE grown GaN LED on Si was demonstrated in 1998 (Guha and Bojarczuk 1998a,b). This work demonstrated that *p*-type doping was achievable in GaN on Si too, and devices could be made out of it. Nevertheless, till recently, the properties of GaN on Si were rather poor and the FWHM of X-ray rocking curve of GaN on Si was 1000 arc s whereas for GaN on SiC it was 250–300 arc s. Photoluminescence spectra of the films grown on Si also show peak broadening. However, during the last couple of years, intensive research activities have been carried out in this area and at present the best GaN layers on Si are almost comparable to GaN layers on SiC.

2. Problems associated with Si

The lattice mismatch between Si and GaN is almost 16% that causes a high dislocation density in the GaN layers but the major problem is the thermal mismatch, which is 54%. Therefore, thick epilayers of GaN for device fabrication are not achievable without cracks.

Furthermore Si is available with resistivity up to 10^4 ohm-cm that is much less than the resistivity value of sapphire, SiC or GaN, and this may lead to parasitic capacitance effects during high frequency operation.

There are also several reports (Hashimoto *et al* 1997; Marchand *et al* 1999) of melt back etching of Si during GaN growth. Under H_2 gas flow, at a temperature of around 1200 K, Si substrate out-gases Si and, during growth, this Si will lead to a high *n*-type background doping making it difficult to achieve *p*-type doping. However, by using NH_3 pre-treatment of Si wafer before growth of GaN layer, this effect can be reduced. Nitridation of Si is self-limiting and the nitridation process will create a thin layer (few nano meters) of Si_xN_y layer and will oppose the Si out-diffusion during growth.

3. Different approaches for growth

(I) GaN growth on sapphire, SiC or Si uses a seed layer or buffer layer to accommodate the lattice mismatch between the substrate and the epilayer. The effect of surface pre-treatment by exposure to NH_3 has been studied for 6H–SiC, 4H–SiC and 3C–SiC substrates for GaN growth (Lee *et al* 2000). After nitridation of SiC, the deposited GaN film was found to be polycrystalline. In case of pre-adsorption of TMG, epitaxial but island-like GaN formed on the substrate. In the third case, with an ultra-

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thin (~ 1·5 nm) coverage of AlN on SiC (by pre-adsorption of TMA or by 50 s deposition of AlN), GaN epilayers were successfully deposited on SiC. However, for growth of GaN on Si substrates, a 20–30 nm thick AlN seed layer deposited well below the actual growth temperature of GaN on the substrates yields epitaxial quality GaN. Occasionally, before AlN predeposition, a few monolayers of Al are deposited over the substrate, which act as barrier for the nitridation of the Si substrate (Dadgar *et al* 2000a). Chen *et al* (2001) performed an extensive study on this topic and they showed that an optimum time of AlN predeposition leads to a steplike surface, deposition for a shorter time produces island growth of AlN and too long a growth time will end in a roughened surface of AlN. The surface roughening is due to the alloying reaction between Al and Si. The AlN predeposition for very short time may lead to nitridation of the Si substrate surface. Therefore, their novel idea was to protect the Si surface by depositing few monolayers of Al, which would be converted into AlN when exposed to ammonia. The reason for depositing low temperature AlN seed layer is to minimize the decomposition of GaN deposits on the reactor wall, which will influence the AlN seed layer growth. Low series resistance is one of the key factors for devices but AlN is a high resistivity material. But at low temperatures, the growth of the seed layer will result in non-stoichiometric composition and also produces a high density of imperfections in the structure, thereby lowering the barrier between the Si/AlN interface. GaN LEDs on Si have been shown to have the lowest series resistance using a low temperature seed layer (Dadgar *et al* 2002a). Thus, either pre-treatment or AlN seed layer will produce a nitrided buffer. However, the AlN seed layer seems to be most effective solution to the problem of mismatch.

(II) The main difficulty in growing GaN on Si is the stress that develops during growth. Cracks occur even for epilayer thickness of about 1 μm. Therefore, to achieve GaN based devices, it is important that the strain be minimized. For optoelectronic devices, a thick layer with good electro-optical and structural properties is required and these are also the basic criterion for films for transistors. Also, to achieve high carrier mobility the interface should be defect free, abrupt and smooth. This is achievable only for epilayers well above 1 μm in thickness. Stress has another influence on device processing. It produces curvature of the wafer and during contact lithography the curvature creates problems. Usually the curvature of GaN on Si is about 2 m (Dadgar *et al* 2000b; Feltin *et al* 2001a). In case of heteroepitaxy, growth starts with small nuclei, which grow and coalesce. At the coalescence boundaries tensile stress of the order of 0·1–0·2 GPa/μm is generated during GaN growth on sapphire (Amano *et al* 1998; Hearne *et al* 1999; Etzkorn and Clarke *et al* 2001) and this generates cracks in the epilayer for thicknesses > 5 μm! The stress increases during cooling and at room temperature it becomes 0·8–0·9 GPa/μm. During epilayer growth of GaN on Si compressive stresses are generated. Fu *et al* (2000) showed that the residual stress is dependent on the impurity concentration in the film and it was observed that doping could enhance the tensile stress in the epilayer (Romano *et al* 2000; Terao *et al* 2001). If the tensile stress is comparable to the compressive stress generated due to thermal mismatch, crack free thick GaN epitaxy on Si will be possible. It is estimated that Si doping conc. of 5×10^{18} in GaN and AlGaN can generate 0·5 GPa/μm tensile stress (Terao *et al* 2001). Thus, an approach that combines doped layers and lower temperature growth can result in GaN films with low stresses.

(III) Substrates containing amorphous or gliding layers e.g. SIMOX or SOI, have great potential for use in GaN growth. Slipping of the crystal over the amorphous layer will effectively lower stresses that develop during growth. Steckl *et al* (1996) converted the thin top layer of Si (111) of a SOI substrate into SiC by carbonization. This was then used as a substrate for GaN in MOVPE. This method produced very high quality material with FWHM of X-ray rocking curve around 360 arc s. Cao *et al* (1997, 1998) also used compliant substrates like Si (100) and nitrided the surface before GaN growth. FWHM of Bragg reflection was 366 arc s in this case but the surface was rough and hillocks were also produced. Some other groups also took a similar approach to reduce the stress by nitrogen implantation of a Si (100) substrate (Koh *et al* 2000) and obtained good results. Therefore, the use of compliant substrates for GaN growth seems to be promising, as the quality of material is comparable to that grown on SiC or sapphire.

(IV) Patterning substrates by masking or etching the substrates or buffer layer is another low cost but highly effective way to reduce the stress or cracks. Dislocations or cracks will be guided in the masked or etched layer and will leave the epitaxial layer with low density of dislocations or cracks. In this technique, Si_3N_4 or SiO_2 layer is deposited over the Si substrate in a patterned manner or deep trenches are made on the masked materials. Ultimately, lateral epitaxial overgrowth (LEO) takes place and the reports show that thick GaN film can be grown easily (Zamir *et al* 2001a). The quality of the material is good enough with reference to the PL intensity (Zamir *et al* 2001b,c). Intensity of PL and FWHM of X-ray rocking curve are comparable to the material grown on SiC for a field area of $200 \times 200\ \mu m^2$ as shown by Honda *et al* (2002). This approach is promising but suffers from the fact that rather small areas can be grown. However, repeated application of this approach to each LEO layer could produce a large area low defect density GaN layer on Si.

(V) The use of AlGaN buffer layers on AlN seed layer is another interesting way to achieve crack-free thick GaN layers. The AlGaN layer increases the series resistance and generates compressive stresses in the GaN layer, which helps to reduce cracks in the layer and provides good electrical insulation from the substrates. So the efficiency of high frequency transistors and vertically contacted LEDs will increase. 1 μm thick GaN layer prepared by this technique has shown an X-ray FWHM of 600 arc s and a PL FWHM of 8 meV (Ishigawa *et al* 1999a,b). The relative brightness of LEDs on GaN on Si is much higher in this method than in the others. The LED was rated at 20 μW at 20 mA (Egawa *et al* 2002a).

(VI) A superlattice structure reduces dislocations. This idea can also be applied to growth of GaN where dislocations tend to bend at the interfaces and they recombine and are some times annihilated by other dislocations. So the superlattice structure of AlGaN/GaN can be used to reduce the cracks and dislocations in a thick GaN layer. Also, another advantage is that this superlattice structure can be used as a Bragg reflector in LED structures. A dislocation density 10 times lower than a normal GaN on Si sample was achieved by using a 15-fold superlattice structure of AlGaN/GaN having thickness of 0·9 μm (Dadgar *et al* 2001). The top GaN layer in this case yielded 0·35 GPa/μm tensile stress only. AlN/GaN superlattice structures are also used as buffer layers to reduce the dislocations and a crack free 2·5 μm thick GaN layer for LED fabrication has been demonstrated (Feltin *et al* 2001b). Thus, with the developments of these varied approaches to growing GaN on Si substrates, the emergence of low cost GaN devices is a matter of time.

4. Devices

III–Vs and other group III nitrides have been mainly investigated for their optoelectronic properties. However, the optical properties for these films grown on Si are not good enough and currently only electronic devices are made from GaN on Si. Waveguide structures and surface acoustic waves (SAW) devices from group III nitrides (Schenk *et al* 2001) are other research areas of interest. Commercialized GaN FETs and LEDs grown on Si are also now available. Considerable research is being carried out on GaN HEMTs at present.

4.1 *Light emitting diode*

Guha and Bojarczuk (1998a) were the first to make MBE grown GaN LEDs on Si, which demonstrated Si as an interesting substrate for GaN growth. But the film had several cracks and the efficiency was poor. With the recent developments in this field, along with the advancement in buffer layer or masking or superlattice structures, the efficiency as well as the output power has increased to a level sufficient for commercialization of GaN/Si LEDs. To reduce the absorption of light in the Si substrate, the simplest way is to use wet chemical etching of the substrate and then mounting the epilayers on some metal base. Output power in such structures also increases effectively. Blue LEDs on Si (111) by InGaN/GaN multiquantum well in MOVPE was first reported by Tran *et al* (1999) and the device worked at 4 V. Using SiO_2 masking techniques to reduce the cracks, MOVPE was used to produce films with defect density comparable to films on SiC substrates. These LEDs had a turn-on voltage of 3·2 V (Yang *et al* 2000) and their series resistance was also smaller than in earlier work. By nitridation of AlAs buffer layers on Si (111) and using a single quantum well it was possible to get bright luminescence (Dadgar *et al* 2000a) with Pt *p*-type contact and Al/Au *n*-type contacts. Thick AlN and AlGaN buffer layers were used by Ishigawa *et al* (Ishigawa *et al* 1999b; Egawa *et al* 2002b) which prevented cracking and the LED power output was 23 μW at 20 mA. With the same buffer layer thickness, they increased the thickness of GaN layer and achieved series resistances as low as 100 ohms. They also investigated vertical contact LEDs (Egawa *et al* 2002b) with series resistance of around 30 ohm. Remarkable work has been done in this regard by Dadgar *et al* who achieved output power of 155 μW at 20 mA. They used low temperature AlN interlayer over 2″ Si (111) substrate and also applied Si_xN_y masking on the AlN interlayer (Dadgar *et al* 2002a). Application of Si_xN_y and AlN buffer reduced defect densities by almost 10 times (Dadgar *et al* 2002a,b). Vertically contacted LEDs with 420 μW at 20 mA have been achieved by device structure modification.

Though the work on GaN LEDs on Si has advanced, they are still not comparable to GaN LEDs on SiC or sapphire. The efficiency as well as the brightness for GaN LEDs on SiC and sapphire is quite high. They can emit 10 mW at 20 mA (after packaging), which is still a distant goal for LEDs on Si substrate. But the reported output power for GaN LEDs on Si are from the labs and not from industry level. Therefore, it may be possible that after epoxy packaging of the LEDs the output power will increase, as in the case of SiC or sapphire based LEDs. Also, the Si substrate can be removed easily from the above layer, which is not easy for sapphire or SiC; thereby, the absorption due to substrate can be checked. Finally the freestanding layer can be mounted on highly reflective metallic bases, which will act as heat sinks for high brightness LEDs.

4.2 *Transistors*

GaN on Si is quite popular for use in HEMT and FET like devices. The background carrier concentration is much lower in GaN on Si than on SiC or sapphire. Also, Si is a better conductor for heat than sapphire. AlN or Al-rich buffer layers can achieve electrical insulation from the substrate. The most interesting thing in HEMT or FET for GaN is that a 2D electron or hole gas forms at the AlGaN/GaN or InGaN/GaN interface without modulation doping. This happens due to spontaneous polarization and strain induced piezoelectric fields. Normally the 2D-carrier sheet density is around $10^{13}/\mathrm{cm}^2$ and the mobility is around 1600 $\mathrm{cm}^2/\mathrm{Vs}$ at room temperature (Semond *et al* 2001). The simple FET structure consists of a thin AlN seed or nucleation layer followed by a thick GaN buffer layer. In order to achieve 2D electron or hole gas, a thin AlGaN layer is deposited on top of it (Kaiser *et al* 2000; Schremer *et al* 2000). A HEMT having a cutoff frequency of 12·5 GHz and a saturation current of 0·91 A/mm (Javorka *et al* 2002) has been developed on GaN/AlGaN 2D electron gas where Si was used as a substrate. The problem with Si is that it is a poor insulator compared to sapphire and SiC. For better insulation one has to make the buffer layers thicker but this will promote cracking. Therefore, a simpler solution could be to dope the GaN buffer layer with deep levels to increase its insulation property, thereby creating semi-insulating GaN.

5. Summary

In the last few years, GaN growth on Si has increased rapidly and several solutions are emerging to accommodate the stress due to thermal mismatch. LEDs and FETs are now well developed and expected to be commercialized soon. A blue laser on Si has been reported by a joint collaboration of RWTH Aachen with AIXTRON AG (Germany) and Stephanov Institute of Physics (Press release: AIXTRON). But its lifetime is not high enough to commercialize it at present. In the near future, Si may be the dominant substrate material for GaN growth due to its low cost and availability in large diameters. The additional advantage is that the Si substrate can be etched away for laser or LEDs. Also, Si can serve as a substrate to grow GaN template on it by HVPE (Lahrèche *et al* 2001) for development of GaN substrates.

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