example about 120 nm, from the Si substrate surface. Implantation energy of about 15-30 KeV and fluences of 1 or 2×10^{16} cm^{-2} can produce acceptable implant results. After the implantation, the Si surface is cleaned using an RCA standard cleaning procedure, followed by dipping of Si samples in diluted HF solution and immediately loading into a growth chamber, without using an elevated temperature (not exceeding 300° C.) at any stage of the cleaning. Generally, a temperature as close as possible to room temperature, or about 80° C. as in the RCA standard clean can be used. Importantly, the cleaning procedure does not involve a high temperature anneal, such as has been used in the growth chamber to ensure removal of any surface oxide contaminants prior to epitaxial growth.

Since the thermal stability of the He bubbles is relatively low, this low temperature cleaning technique is important to achieve the beneficial results according to this embodiment of the invention. Then, an AlN buffer layer is formed on the Si substrate at a relatively low temperature of about 380-750° C., for example 680-720° C. Simultaneously this AlN growth temperature also serves to anneal the implanted Si substrate. At this temperature, the implanted He ions coalesce into He bubbles at a specific distance from the Si substrate surface (being determined by the implantation fluence and energy) such that misfit dislocations formed at the AlN/Si interface can interact with strain field formed around the He bubbles. Under these conditions, the He bubbles form neither too close nor too far from the Si surface, in which case they could either dissipate to the surface or be too far from the newly formed misfit dislocations for their strain fields to interact with them, respectively. The dislocations thus primarily move into the Si substrate (as threading dislocations) instead of into the AlN epi-layer. Finally, the GaN layer of interest is grown on the AlN surface. Molecular Beam Epitaxy (MBE) is a suitable technique for accomplishing the relatively low temperature growth required for this embodiment of the invention.

In accordance with the invention, since the strain due to the lattice mismatch has been substantially dissipated by the misfit dislocations directed into the Si substrate, the GaN growth layer can grow with a substantial decrease of structural defects. In this way, strain relaxation at the buffer/Si interface can lead to the formation of larger grains than those observed in the GaN/AlN layers grown on un-implanted Si under the same conditions. Some dislocations will still likely remain in the GaN/AlN layer mainly due to the difference between the thermal expansion coefficient between Si and the layers grown on top of it, but with much lower density than for the growth on un-implanted Si. The distribution of the remaining dislocations in the AlN/GaN layers is uniform throughout the wafer, as opposed to laterally or pendeo-epitaxially overgrown layers, which are also able to decrease defect density in GaN grown on foreign substrates. In the present approach, however, the devices can be uniformly distributed.

The invention enables fabrication of improved integrated devices based on GaN (or other III-Nitride like InGaN or AlGaN) grown on Si, such as continuous wave (CW) lasers and light emitting diodes, at reduced cost.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1**(*a*) is a schematic illustration of a process of fabricating a GaN semiconductor device substrate in accordance with a specific embodiment of the present invention in which He is the implanted ion, and the resulting GaN semiconductor device substrate; (b) For comparison, a process of fabricating AlN/GaN on unimplanted Si and expected defect distribution in a GaN layer.

FIG. **2** is a plot showing results of channeling measurements performed on Si implanted with 15 keV of He ions, up to a fluence of 1×10^{16} He/cm^2, after RTA annealing for 120 s at different temperatures: 350° C. (open triangles), 450° C. (open circles), 600° C. (full diamonds), 750° C. (dashed lines), 1000° C. (solid line).

FIG. **3** is a plot showing channeling spectra after 600° C. RTA annealing (rapid thermal annealing) for 120 sec for the Si samples implanted with different energies: 15 keV through a 50 nm SiO_2 cap (full diamond), 15 keV (open circles), and 30 keV (dashed line). All samples were implanted with 1×10^{16} He/cm^2. For comparison the Si sample implanted with 15 keV up to the fluence of 2×10^{16} He/cm^2 is shown as the solid line.

FIG. **4** depicts a cross-section TEM micrograph of GaN/AlN grown on He implanted Si (15 keV and fluence of 1×10^{16} cm^{-2}; the He bubbles are about 120 nm from the interface). An interaction of misfit dislocations with the strain field (and possible dislocation loops) formed around the He bubbles is visible. End-of-range defects are indicated by arrows.

FIG. **5** depicts a higher magnification image of a portion of the micrograph of FIG. **4** showing the area close to a void formed at the interface. Note the lack of misfit dislocation interaction in this area. Arrows outline a band of He bubbles.

FIG. **6** depicts a cross-section micrograph from the GaN/AlN layers grown on implanted Si substrate (30 keV and fluence of 1×10^{16} cm^{-2}) showing misfit dislocations redirected into the Si substrate. Some dislocations propagated farther into the Si substrate (beyond the end-of-range defects).

FIG. **7** depicts electron diffraction patterns of GaN grown on un-implanted (a) and implanted (b) Si substrate cleaned using a procedure in accordance with the invention, described herein (1×10^{16} cm^{-2} He).

FIG. **8** is a plan-view micrograph of GaN grown on He-implanted (1×10^{16} cm^{-2}) Si substrates (with AlN buffer layer) showing large grain diameter. The subgrain diameter (with dislocations on grain boundaries) is more than 1000 nm.

FIG. **9** is a plan-view micrograph from the GaN layer grown on un-implanted Si (with AlN buffer layer) taken with multi-beam conditions to observe all grains in contrast. Growth conditions and cleaning procedure II were the same for the growth on the implanted (FIG. **8**) and un-implanted (FIG. **9**) Si.

FIG. **10** depicts X-ray rocking curves comparing implanted (two different implantation energies—for sample number #2541-15 keV and 1×10^{16} cm^{-2}; #2452-30 keV and 1×10^{16} cm^{-2}) and non-implanted sample #2440.The line intensity and FWHM (full width at half maximum) give information about sample quality. It can be seen that line intensity is about 4 times higher with 3× narrower FWHM for implanted samples. This clearly suggests structural quality improvement with application of the inventive method.

DETAILED DESCRIPTION OF SPECIFIC EMBODIMENTS

Reference will now be made in detail to specific embodiments of the invention. Examples of the specific embodiments are illustrated in the accompanying drawings. While the invention will be described in conjunction with these specific embodiments, it will be understood that it is not intended to limit the invention to such specific embodiments. On the contrary, it is intended to cover alternatives, modifications, and equivalents as may be included within the spirit and scope of the invention as defined by the appended claims.