Current Opinion in Solid State and Materials Science 19 (2015) 49–67

Contents lists available at ScienceDirect

Current Opinion in Solid State and Materials Science

journal homepage: www.elsevier.com/locate/cossms

Advances in ion beam modification of semiconductors

R.G. Elliman *, J.S. Williams

Department of Electronic Materials Engineering, Research School of Physics and Engineering, Australian National University, Canberra, ACT 0200, Australia

ARTICLE INFO

Article history:
Received 3 September 2014
Revised 24 November 2014
Accepted 28 November 2014
Available online 16 December 2014

Keywords:
Ion implantation
Semiconductor
Silicon
Germanium
Silicon carbide
Zinc oxide
Gallium nitride

ABSTRACT

This review provides an overview of the current status of ion-implantation research in silicon, germanium and the compound semiconductors SiC, GaN and ZnO. The discussion of silicon includes recent developments in metrology and device simulation, as well as a brief discussion of emerging applications in photovoltaics and quantum electronics. That of Ge includes a more detailed overview of doping, radiation damage and annealing processes due to the renewed research interest in this material. Finally, the discussion of compound semiconductors focuses on the newer wide bandgap materials where there are remaining implantation issues to be solved and potentially new implantation applications emerging.

1. Introduction

The application of ion-implantation to semiconductors is dominated by silicon-based microelectronics, and specifically by the manufacture of silicon-based digital electronics and memory devices. This has been the case since the early 1970s when ion-implantation began to replace diffusion as the primary method of doping silicon [1,2]. Developments over the subsequent decades have only reinforced the dominance of the ion-implantation technique to the point that it is now difficult to image device fabrication without it [3]. Throughout this period ion-implantation has also found other important semiconductor applications, including: the manufacture of semiconductor-on-insulator (SOI) substrates using hydrogen-induced cleavage or buried oxide synthesis by oxygen implantation; electrical isolation of devices in high speed III–V electronics; and lifetime control in SiC power electronics.

Because of its long history and incremental development, most issues associated with ion-implantation in silicon have been well researched. This does not mean that there are no new challenges or that the existing understanding cannot be improved but it does mean that much of the research effort is now directed at process optimisation, modelling and simulation rather than fundamental understanding. The situation for Ge is somewhat different as it has not received the same attention as Si and is only now being considered for integration into mainstream devices. This has led to a renewed interest in ion-implantation of this material and to new insight into dopant activation and defect annealing mechanisms. Finally, ion-implantation into compound semiconductors has been limited to just a few niche areas of application due to the complexity of defect annealing and dopant activation in these materials. However, there remains significant interest in newer wide bandgap materials (e.g. SiC, GaN and ZnO) where the understanding of basic processes remains immature and where potential new implantation applications are emerging. This review considers recent developments in ion-beam modification of semiconductors in this context.

2. Silicon

As noted above, the main application of ion-implantation is silicon-based microelectronics, and specifically the fabrication of digital electronics and solid-state memory devices. These applications typically involve around 40–60 ion-implantation steps employing as many as 20 implant species, and cover ion energies in the range from a few hundred eV to several MeV, and ion-fluences in the range from order $10^{11}\,cm^{-2}$ to order $10^{16}\,cm^{-2}$, as shown in Fig. 1. Of these, around 45% involve doping, 20% involve threshold-voltage adjustment, 20% involve diffusion control (e.g. pre-amorphization, co-implantation), 10% involve reliability improvement (e.g. etch rate control, mask-edge roughness control) and 5% involve contact-resistance and work-function adjustment. It is clear from these statistics that doping remains the main application of ion-implantation but it is important to note the growth of

---

* Corresponding author. Tel.: +61 2 6125 0521; fax: +61 2 6125 0511.
E-mail address: rob.elliman@anu.edu.au (R.G. Elliman).

http://dx.doi.org/10.1016/j.cossms.2014.11.007
1359-0286/

non-doping applications as these are becoming increasingly important for improved device performance and process control [3–5]. Other specialist applications relating to silicon-based microelectronics include the fabrication of semiconductor-on-insulator (SOI) wafers by hydrogen-implantation induced cleaving [6].

2.1. Dopants, defects and their interactions

The ability to produce tailored doping profiles is fundamental to the success of ion-implantation but is compromised by the need to anneal the radiation damage produced by the implanted ions. The damage is detrimental to device performance and must be removed by annealing to achieve optimal performance. However, this must be achieved without significant dopant diffusion and is complicated by interactions between defects and dopants that can give rise to enhanced dopant diffusion and deactivation at various stages of the annealing cycle [7]. The understanding of these processes and the optimisation of annealing regimes to remove defects and minimise dopant diffusion have been a major research focus since the beginning of the field. Developments in this area are inevitably driven by the demands of device scaling and new device architectures. These currently include the need for shallower and sharper dopant profiles with higher levels of dopant activation, the ability to anneal implant-related defects with reduced thermal budgets, and the ability to control these in complex three-dimensional, heterogeneous device architectures. These requirements have also led to the need for new methods of characterisation and a greater reliance on atomic-scale modelling and simulation.

A broad range of strategies have been developed to meet current demands [3,5,8,9], including: the use of pre-amorphization implants to avoid ion-channelling, and enable damage recovery by solid-phase epitaxial regrowth at low temperatures; the use of high-mass dopant ions such as In and Sb to tailor junction abruptness; the use of shorter-time, higher-temperature annealing regimes (rapid-thermal annealing, spike annealing, flash annealing and microwave annealing) to achieve dopant activation and defect annealing while minimising dopant diffusion; co-doping with impurities such as F and C to trap Si-interstitials and reduce defect-dopant interactions (i.e. clustering, deactivation and transient enhanced diffusion (TED)) [10]; and the use of high-mass ions (e.g. Ge or Xe) or cryogenically cooled wafers (⩾ −100 °C) to increase the abruptness of amorphous–crystalline interfaces and thereby reduce the concentration of end-of-range defects [11]. Applications involving 3D device architectures (e.g. finFETs) may also require additional strategies such as wafer heating during implantation to avoid amorphization of large aspect-ratio structures that are difficult to recrystallize by solid-phase epitaxy [12].

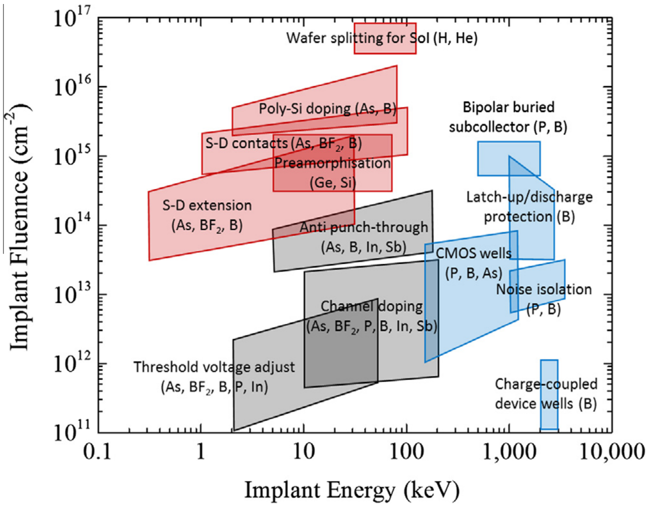

Fig. 1. Implant energies and fluences employed in typical integrated circuit manufacture with species listed in order of decreasing usage. The colours indicate the ranges covered by typical low- (red), medium- (black) and high-energy ion-implanters. (after L. Rubin and J. Poate, Industrial Physicist, pp. 12–15, June/July 2003).

These strategies are based on the current understanding of dopant diffusion, defect annealing, dopant–dopant interactions and dopant–defect interactions [13], and build on knowledge gained over many decades. This understanding has recently been reviewed by Aboy et al. [14] and when combined with the earlier review by Pelaz et al. [13] provides a comprehensively overview of defects, dopants and their interactions. The interested reader is referred to these reviews for further detail about these processes and ongoing developments. However, one area not covered by these reviews is the effect of stress on atomic scale processes, an area that is of increasing importance in modern device structures and an area where there have been recent developments [15]. This significance of such effects is briefly reviewed here.

Regions of a semiconductor device can be subjected to enormous stress (∼GPa) either by design to improve device performance or as an indirect consequence of thermal processing (i.e. the differential thermal and mechanical properties of various embedded, abutted and deposited materials) [15–17]. Stresses and strains can have a significant impact on: point-defect formation and diffusion [18–20]; dopant solubility and diffusion [18–23]; nucleation, growth and spatial distribution of intermediate and extended defects [24–26]; and the recrystallization of amorphous layers [27–30]. The thermodynamic framework for understanding the effects of hydrostatic and biaxial stress on point defects and dopants was outlined by Aziz [20] and a recent experimental example is provided by Bennet et al. [22]. They compared the effect of tensile strain (0.7%) on the electrical activity of As and Sb in ion implanted Si samples and showed that it produced a significant enhancement of the Sb solubility while having no significant effect on the As solubility. This behaviour was attributed to the fact that Sb has a larger covalent radius than Si and that it could act to relieve tensile strain in the substrate. In contrast, substitutional As was expected to slightly increase the tensile strain and as a consequence showed no significant solubility enhancement. The resulting Sb solubility was found to approach 10^{21} cm^{-3}, more than twice that achieved in unstressed material. Such an enhancement clearly has important implications for device performance.

An understanding of the effects of stress on the nucleation, growth and motion of intermediate and extended defects is of particular interest as these evolve from point defects during annealing and are the most likely to be present in the final device structure [31,32]. Such effects are highlighted by the work of Swadener et al. [25] who performed large-scale computer simulations to investigate the aggregation of self-interstitials in ion-irradiated silicon subjected to stress. They found that {1 1 1}-oriented planar defects were dominant under stress-free or compressive conditions, while {1 1 3} rodlike and planar defects were dominant under tensile conditions. Since these intermediate defect complexes act as precursors for dislocation growth, changes in their orientation and density are expected to have a direct effect on subsequent defect evolution. It is also well known that dislocation velocities in silicon are affected by stress [33] and doping [34]. In assessing their impact on device performance it is also important to take into account the stress associated with the defects themselves as this can have a direct effect on device performance. For example, Lim et al. [35] have shown that mask-edge dislocations resulting from solid-phase-epitaxy can be used to create tensile strain in the channel of a field-effect-transistor to provide a 40–60% improve-