Implant Damage Engineering for Advanced Device Fabrication

Kyungwon Lee
Axcelis Technologies Inc.
#401, Digital Station, 31-2 Seokwoo-dong, Hwasung-si, Kyunggi-do 445-170, Korea
kyungwon.lee@axcelis.com

Leonard M. Rubin
Axcelis Technologies, Inc.
108 Cherry Hill Drive, Beverly, MA 01915 USA

Abstract

Damage engineering, or controlling the evolution of extended defects after the annealing of ion implantation induced damage, is essential for advanced devices. Implant induced defects affect dopant diffusion, activation, and device leakage. The key implant variables affecting damage engineering are dose rate, duty cycle, and the mass of the implanted ion. Of these, dose rate has the largest effect on damage engineering.

Introduction

Ion implant injects dopant into the silicon substrate, generating crystal damage in the process. Upon annealing, these point defects for extended defects (fig. 1). As devices continue to shrink, implant damage increasingly affects dopant placement and defect formation, which in turn affect device performance. As a result, we need to better understand ion implant damage and how to control it in order to improve device performance for advanced nodes.

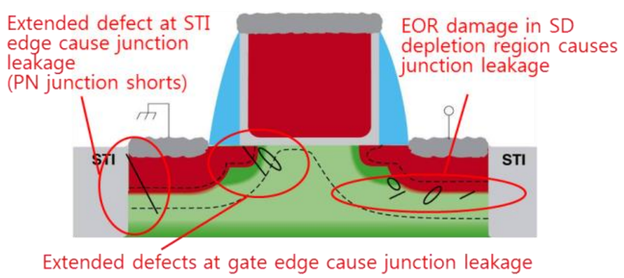


Figure 1. Extended defects resulting from implant damage

Factors Affecting Implant Damage

For high dose, implants, the total amount of implant damage is well correlated to the amorphous layer thickness (ALT). The various factors that affect implant damage or damage engineering include ion mass, energy, dose, dose rate, implant temperature, and duty cycle (table 1). However, energy, dose, and to a certain degree ion mass are fixed by process requirements. This leaves dose rate, duty cycle, and (to some degree) ion mass as adjustable parameters for damage engineering.

Instantaneous dose rate is defined as the rate of arrival of ions to the surface when the beam is on a given location (ions/cm^2/sec.). As the dose rate increases, ALT also increases. ALT increases with decreasing implant temperature. Duty cycle is time the beam is on a given location divided by the total implant time (units are percentage). ALT also increases with increasing duty cycle. For the mass of the ion, we discuss molecular implantation to enhance damage engineering.

Table 1. Factors affecting implant damage

Parameter	Value for Thicker Amorphous Layer
Instantaneous dose rate	High
Wafer temperature	Low
Duty cycle	High
Mass / Energy / Dose	High
Amorphous Layer Thickness (ALT)	Goal: Thicker ALT

Control of Implant Damage

Because amorphous layers regrow with fewer extended defects than crystalline material, a thicker amorphous layer will have fewer extended defects after annealing (fig. 2). Lower device leakage and improved dopant activation will result.

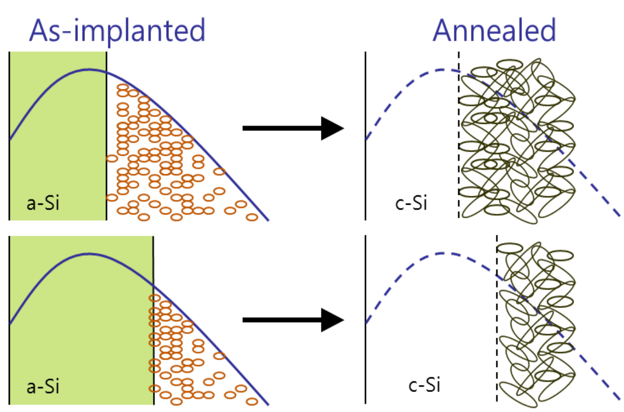


Figure 2. Thicker amorphous layer leads to less end-of-range implant damage

If we use high temperature (~1100°C) annealing, most of the implant damage is eliminated after thermal process (fig. 3). But there are limitations to practical thermal budgets because of device sensitivities. These limits are getting tighter for advanced devices, so implant damage control is becoming more important.

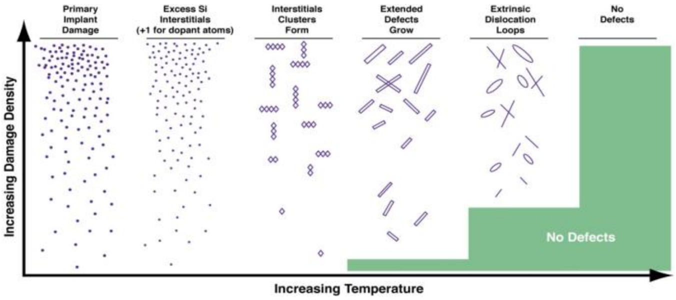


Figure 3. Recrystallization of Implant Damage during Anneal

Damage vs. Implant Temperature

Figure 4 shows the importance of implant temperature on the amorphization thickness of a 6.0 keV carbon implant. At +15 °C there is incomplete amorphization. At +5 °C, the implant shows partial amorphization. At -30 °C there is complete amorphization. Additionally, due to the high dose rate of the spot beam implanter used in this test, the thickness of this amorphous layer is higher than that of a comparable implant on a low dose rate ribbon beam implanter [1].

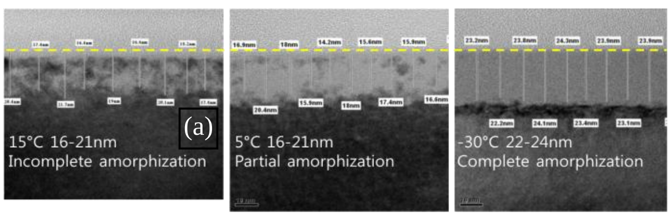


Figure 4. TEM Image of Temperature Test with Carbon 6keV (a) +15°C Incomplete amorphization (b)+5°C Partial amorphization (c)-30°C Complete amorphization

Figure 5 compares a boron 15keV implant between a low dose rate at +20°C and a high dose rate at -50°C. Increasing the dose rate and decreasing the temperature increases the ALT from 52nm to 77nm. low temperature and high dose rate showed the smoother amorphous and crystal interface. Additionally, the smoother interface associated with the higher ALT makes it less likely that threading dislocations will propagate from the amorphous/crystalline interface during annealing. This leads to lower device leakage.

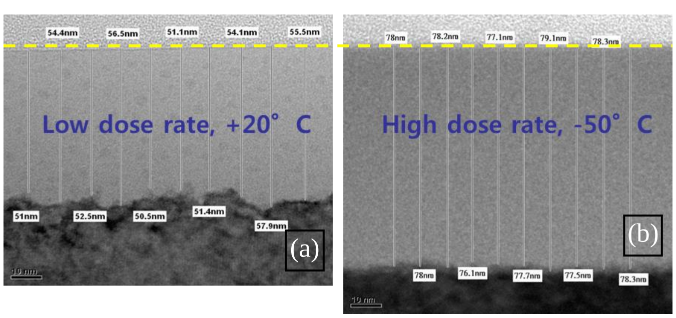


Figure 5. TEM of temperature and dose rate test with boron 15keV (a) Low dose rate at +20°C (b) High dose rate at -50°C

Damage vs. Dose Rate

In general, implant damage is well correlated to and measured by amorphous layer thickness. Fluorine, which is always present in BF_2 implants, is highly mobile at annealing temperatures and naturally decorates crystal damage after annealing. This makes F a fairly sensitive indicator of residual implant damage. Figure 6 shows the fluorine SIMS profiles for a BF_2, 25keV implant and 925°C furnace anneal. The smallest of the F peaks is decoration of the damage at the location of the amorphous/crystalline interface. The integrated area and position of this peak are directly proportional to the amount of damage and the position of the amorphous/crystalline interface, respectively. Figure 6 clearly indicates an exponential decrease in the area of the peak and a increase in the depth of the peak with decreasing temperature and increasing dose rate (beam current). It is also seen how these two parameters are additive, such that they can offset one another to achieve the same result or be combined to effectively eliminate the damage (bottom curve in Fig. 6). Also note that thicker amorphous layers are strongly correlated with significantly lower defect levels.

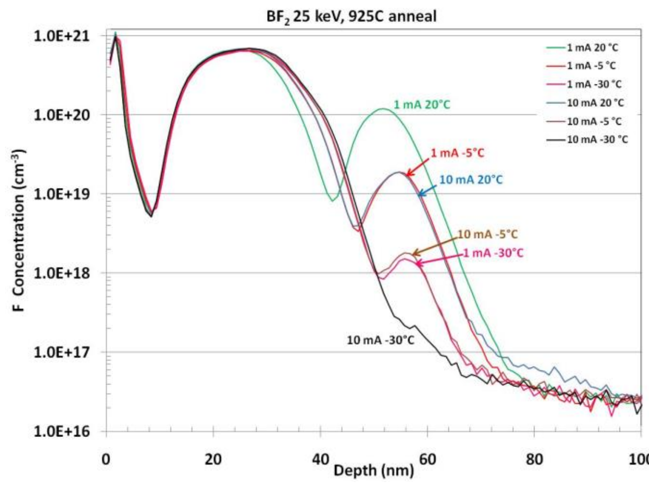


Figure 6. Fluorine decoration of residual damage at the amorphous/crystalline interface as a function of dose rate and wafer temperature

Damage vs. Monomer or Molecular Implant

Figure 7 indicates that lighter species have amorphization thresholds (for a given dose) at significantly lower temperatures and/or higher dose rates than heavier species. While the chemical element used in a particular implant is determined by device considerations, this raises the possibility of replacing a monomer (single) ion of this species with a much heavier molecule containing this species. BF_2 is an example of such a molecule that has been widely used in ion implantation for decades.

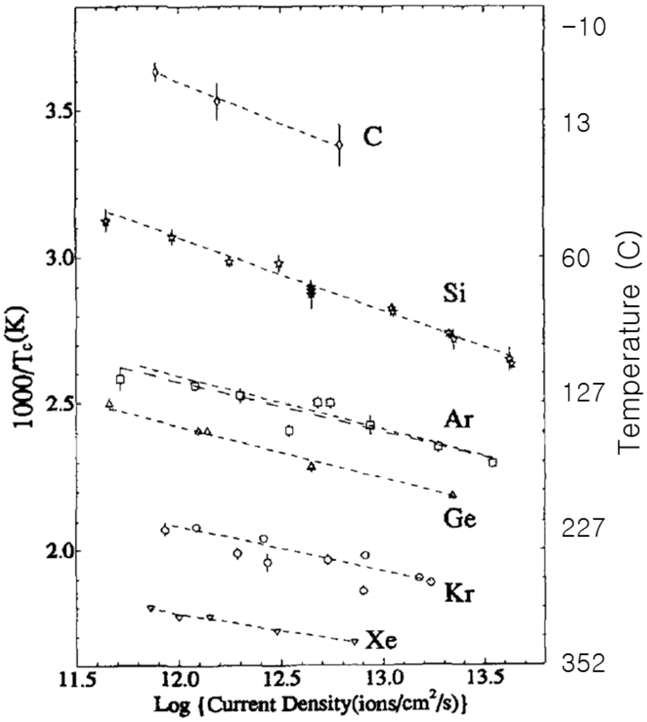


Figure 7. Amorphization threshold vs. dose rate and temperature for several implant species. From Ref. [2]

Figure 8 shows a TEM comparison between monomer carbon and molecular carbon at 3keV equivalent energy. Due to its low mass, monomer carbon does not amorphize at all at +20°C and only weakly amorphizes silicon even at -70°C. In contrast, molecular carbon generates a significant amorphous layer even at +20°C. Because the amorphous layer thickness for molecular carbon barely increases as the implant temperature is reduced from +20 to -70°C, we conclude that the damage engineering from molecular carbon is nearly saturated even at room temperature. This suggests a way to realize the full damage engineering benefits for carbon without the complexity and productivity issues associated with low temperature implants.

Figure 9 shows Therma-wave (TW) and sheet resistivity data for BF_2 with a co-implant (done before the BF_2) of either monomer or molecular carbon at 3.0 keV. In addition to the decreasing TW values with increasing temperature, the TW values are consistently and significantly higher for molecular carbon. This indicates the superior amorphization ability of the heavy C_7H_7 molecule. The sheet resistivity is significantly lower for the molecular carbon pre-implant. This occurs because the thicker amorphous layer leads to more dopant in this layer. Dopant activation is higher in regrown amorphous layers than in damaged crystalline layers, leading to lower sheet resistivity. Also note the decrease in Rs with lower implant temperature, which results from the thicker amorphous layers at lower implant temperatures.

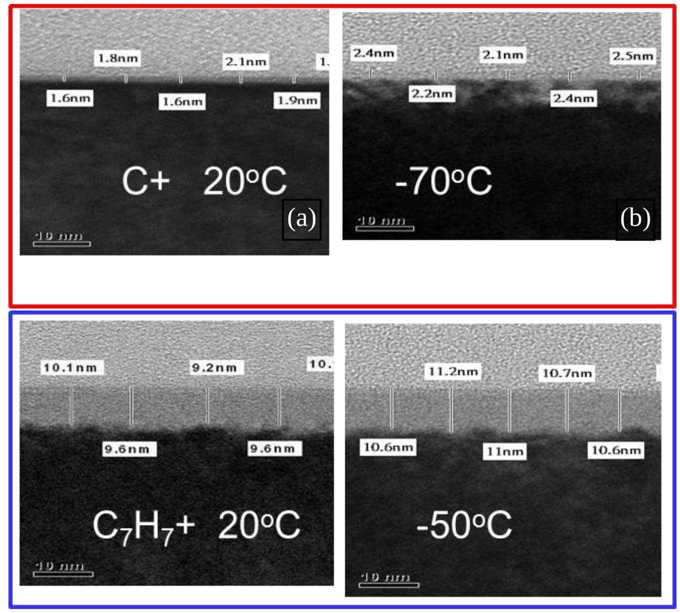


Figure 8. TEM of monomer and molecular carbon implanted at 3.0keV equivalent (a) monomer C at +20°C (b) monomer C at -70°C (c) molecular C at +20°C (d) molecular C at -50°C

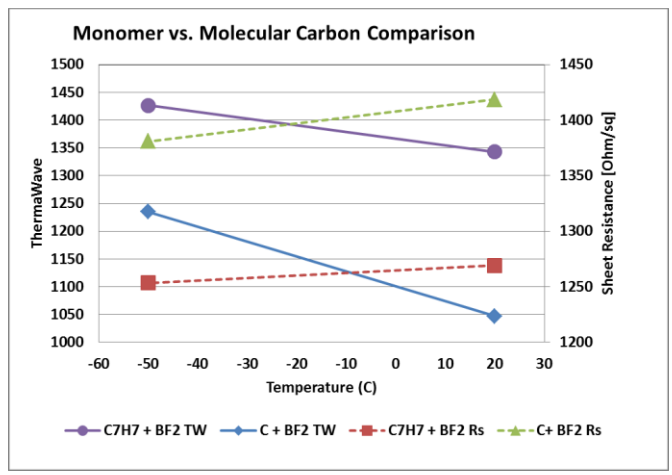


Figure 9. TW and Rs comparison of monomer and molecular Carbon at 3keV with a dopant implant of BF_2 at 2keV

Damage Control by Heated Implant

Low temperatures and high mass molecules have been shown to be effective at increasing amorphization. However, sometimes it is desirable to minimize or prevent amorphization in high dose implants. This is important in FinFETs, where if the narrow fin is fully amorphized, there is no way to regrow the fin into a single crystal. Figure 10 shows an example of using heated implants (400-450°C) to eliminate amorphization during high dose arsenic implantation.

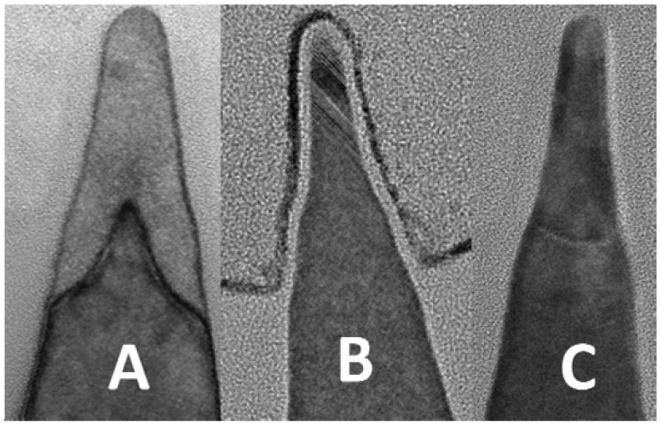
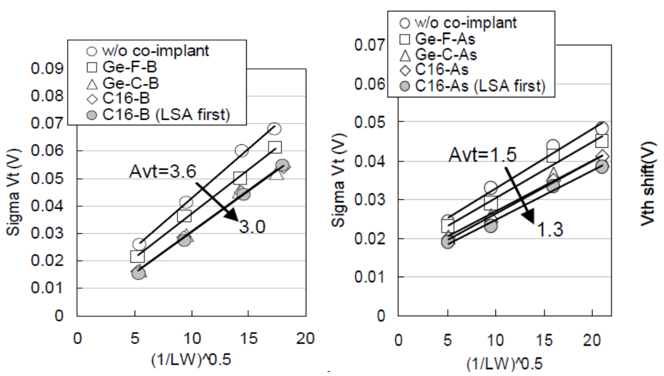


Figure 10. TEM cross section of silicon fins (a) immediately after room temperature implant, (b) after room temperature implant and a spike anneal (1sec at ~1000°C), and (c) after heated implant alone (no anneal) From Ref. [3].

Advanced Device Solution

Figure 11 shows the V_T variation for advanced DRAM peripheral devices with a variety of different amorphizing co-implants prior to the halo implant. The halo implant species is B for the NMOS device and As for the PMOS device. A co-implant using molecular carbon as the species consistently gives lower V_T variation than either sequence of Ge+F or Ge+C. Additionally, a two-implant sequence is replaced by a single implant. The V_T variation is lower for molecular carbon because the thicker amorphous layer and more uniform amorphous/crystalline interface leads to more uniform and precise placement of the subsequent doping implant.

.



(a) (b)

Figure 11. Pelgrom plots of DRAM devices comparing monomer and molecular carbon for the pre-halo co-implant (a) NMOS (b) PMOS. From ref, [4].

Conclusion

Advanced devices require careful damage engineering to optimize device performance. The key variables for damage engineering are dose rate, implant temperature, and the substitution of high mass molecular ions for lighter species. Maximum amorphization is achieved using a high dose rate, low implant temperature, and molecular implants (if available for the species of interest). These independent variables are additive, such that they can be substituted for one another or used in combination to optimize productivity and device performance. For example, the extremely high dose rate of a spot beam significantly increases the temperature at which damage saturates. The result is that damage engineering can be achieved on a spot beam without going as cold as required by a low dose rate ribbon beam. For this reason, spot beam technology is the best way to implement damage engineering for advanced devices.

Acknowledgments

We thank Dr. Michael Ameen and the Axcelis demonstration laboratory for sample preparation and data analysis.

References

[1] J.H.Yi, et al., "Advanced Implantation Technique for Beyond 2X node", *Semicon Korea*, 2010.

[2] R.D. Goldberg, et al., "Amorphization of silicon by elevated temperature ion irradiation", *Nucl. Inst. Meth. Phys.* Res. B 106 p. 242-247 (1995).

[3] L. C. Pipes, et al. (Intel), *Proc. XX Intl. Conf. Ion Implant. Tech.,* p. 39 (2014).

[4] H. Lee, at al., "Effective Reduction of Threshold Voltage Variability and Standby Leakage using Advanced Co-implantation and Laser Anneal for Low Power Applications", 2008 *IEDM Tech. Digest*, p. 913.