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TECHNICAL PROGRESS REPORT

Ion Mixing of Semiconductor Layered-Structures

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Abstract

This research is a collaborative program between the University of California at San Diego and Cornell University to investigate the phenomenon of ion mixing in semiconductor layered structures. The research effort also involves interactions with Oak Ridge National Laboratory under the Surface Modification and Characterization Collaborative Research Center Program (D. B. Poker, C. W. White, and J. R. Roberto).

In the previous period of investigation, we have established the basic ion mixing (IM) characteristics for semiconductor layered structures, in that there is a temperature dependent and a temperature independent regime in ion-mixing of III-V semiconductor systems such as the InGaAs/InP and the AlGaAs/GaAs systems and the Ge/Si system (see Appendix A). During the current period of investigation, we investigated parameters that could affect ion-mixing rates in semiconductors. We found that the use of shallow dopants as the mixing ion did not increase the mixing rate, thus indicating that electrically active ions (or the Fermi level) do not play a significant role in ion-mixing (see appendix A). On the other hand, the presence of mismatch strain in Ge/Si layered structures can affect the mixing rate, especially in the temperature independent regime (see Appendix B). Mismatch strain can also affect the solid-phase regrowth kinetics of amorphous layers of Ge-Si alloys (see Appendix C for details). In summary, we found that ion mixing kinetics depend primarily on the ion and the target mass and the target temperature. Mixing rates can also be affected, to a certain extent, by thermodynamic driving forces (such as the cohesive energy and the stored strain energy of the system). Impurities do not play a significant role in mixing kinetics. During this period of investigation four papers have been submitted or published.

For the next period of investigation, we plan to concentrate on a more systematic investigation of III-V semiconductor systems. We are particularly interested in reducing the damage caused by ion-mixing and in the use of ions that can induce mixing and raise the electrical resistance in the structure simultaneously. With these issues resolved, we should be in a position to use ion mixing for photonic device fabrication. We intend to fabricate semiconductor superlattice waveguides and modulators.

Summary of Results

Some of the significant results are summarized as follows:

- (1) The dependence of ion mixing kinetics on electrically active ions (the Fermi level effect)

The effects of shallow ions on the ion-mixing process were examined using ion pairs of similar masses, with one of the pair being an electrically active ion, i.e. As^+ and Kr^+ or Si^+ and Ar^+ . We found that electrically active ions do not enhance the ion-mixing rate, in marked contrast to the conventional technique of ion implantation at room temperature followed by a high temperature annealing to cause mixing. This fact enables ion-mixing to fabricate planar photonic devices without affecting the conductivity significantly. An example of this observation is shown in the following figure (Figure 1) (see Appendix A for details).

Figure 1. Ion mixing rate vs $1/T$ for AlGaAs/GaAs samples implanted with Si^+ (180 keV) or Ar^+ (190 keV) ions. Within experimental uncertainties, the mixing rates were the same for both ions. The solid symbols represent the net mixing rate, i.e., subtracting the rate below T_c from that above T_c .

(2) The effect of impurities on ion mixing of the Ge/Si system

The influence of impurities such as H, Au, W and O was studied. These impurities were investigated because H tends to saturate dangling bonds in Si and apparently reduces the solid-phase regrowth rate of amorphous Si; Au is an interstitial fast diffuser in group IV semiconductors; W is a compound former with Si and Ge and O almost always slows down all solid phase reactions in Si and Ge. It was found that the impurities mentioned above do not play an important role in the kinetics of ion-mixing over the entire range of the Q curve (the curve of the temperature dependence of ion-mixing, see Appendix B for details).

(3) The effect of the mismatch strain on the ion-mixing in Ge/Si layered structures.

While impurities do not affect the ion-mixing kinetics, the presence of mismatch strains in Ge/Si quantum well structures appears to enhance the mixing rate, especially in the athermal regime. For samples with a thin strained SiGe layer ($\sim 40\text{\AA}$) embedded between Si layers, the thermal mixing is enhanced by a factor of about 2 compared to that of relaxed samples. These results enable us to estimate an excess driving force of about 0.6 eV/atoms for mixing in strained layers. Table 1 shows the comparison of the mixing rate (Dt/ϕ) of strained and relaxed samples (see Appendix B for details).

Table 1
Ion mixing rate at room temperature for strained and relaxed samples

Sample No.	Initial state of as -grown sample	$Dt/\phi (\times 10^{-28} \text{ cm}^4)$	Final state before ion mixing	$Dt/\phi (\times 10^{-28} \text{ cm}^4)$	ratio ^(a)
701	strained	2.34	relaxed	1.24	1.89
601	strained	1.54	relaxed	1.25	1.23
602	strained	1.62	relaxed	0.95	1.71
703	strained	2.58	relaxed	1.63	1.58
201 ^(b)	strained	1.80	relaxed	0.96	1.88
5	<u>unstrained</u>	1.17	relaxed ^(c)	1.10	1.06

^(a)Ratio = $(\frac{Dt}{\phi})_{\text{initial}} / (\frac{Dt}{\phi})_{\text{final}}$

^(b)Structure with 4 periods of strained layers. Dt/ϕ calculated for the second layer from the surface.

^(c)Went through the relaxation process.

(4) The effect of strain on the regrowth rate of amorphous Ge-Si layers

The solid-phase regrowth rate of amorphous Ge-Si alloy layers in a strained structure appears to be reduced, contrary to enhanced ion mixing rates observed in strained Ge/Si layered structures. While ion-mixing of strained layer tends to reduce the stored strain energy in the system, the epitaxial regrowth of amorphous layers in a strained system tends to increase the strain energy (see Appendix C for details).

In summary, our results indicate the ion-mixing kinetics primarily depend on the mass of the mixing ion, the mass of the target and the irradiation temperature. The mixing kinetics can also be influenced to a certain extent by the thermodynamic driving force (such as the cohesive energy and the stored strain energy) in the athermal regime and the kinetic barriers in the thermally activated regime.

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