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Microwave Plasma Doping: As Activation and Transport in Ge and Si

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Abstract

Microwave RLSA™ plasma doping technology has the potential to realize ultra-shallow and conformal doping for extensions of non-planar devices. In this work, we first demonstrate carrier activation for AsH_3 based plasma doping into Si and Ge using by rapid thermal annealing. Depth profile measurements show intrinsic dopant diffusion for plasma doping is much slower than the case of ion implantation. The low diffusion coefficient is explained by the minimization of damage in the RLSA™ process.

1. Introduction

Ultra-shallow conformal doping for S/D extension is required for non-planar devices such as Fin FETs. Plasma doping is a candidate technology for this process. Recently, Ueda *et al*. have reported high activated dose As conformal doping of 10 to 40 nm (AR> 2-4) Si fin structures using a RLSA™ plasma source. [1] The source facilitates doping by supplying low energy ions and dopant radicals to the substrate. As a result, the process is essentially free of physical damage.

High mobility materials such as Ge have gained increased attention for their ability to improve I_{on}. Issues remain regarding parasitic resistance and junction formation. High dopant activation into Ge is necessary to reduce external parasitic resistances including contact resistance [2-4]. Large n-type dopant diffusion coefficients in Ge make n^+/p ultra-shallow junction formation challenging. This is exacerbated by defects or vacancies in Ge that not only enhance diffusion but also suppresses activation [5-7]. That the RLSA™ plasma doping process is damage free makes it well suited to meet the challenges of ultra-shallow n^+/p Ge junction formation.

In this work, we present carrier activation results for As doping of Si and Ge. Conventional rapid thermal annealing is demonstrated to realize a significant degree of activation. By comparing the diffusion behavior of As in Ge for both plasma doping and conventional ion implantation, we show the lower diffusion coefficients in plasma doping are well suited to shallow junction formation.

2. Experimental

The plasma doping apparatus used in this work is presented in Figure 1 [1]. Identical AsH_3 based doping processes were used on p-type Si or Ge (100) substrates. Dopant activation was carried out by annealing at 550-1050 ºC for 60 sec. After Al electrode deposition, sheet resistance (R_s) was measured by standard four-point probe (4PP) and van der Pauw (vdP) methods. We also used the vdP for Hall-effect measurement at room temperature. Dopant and carrier concentration profiles were analyzed by SIMS and SRP (Spreading Resistance Probe).

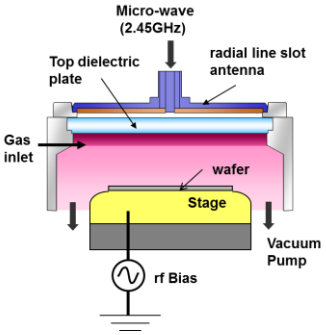


Fig. 1 A cross-sectional view of RLSA™ doping reactor [1].

3. Results and Discussions

3.1 Silicon

Annealing was carried for the silicon samples at three different temperatures. Figure 2 shows higher annealing temperature leads to lower sheet resistance (R_s), higher carrier dose, and therefore increased degree of activation. Since 4PP and vdP derived R_s are consistent (Fig. 2(a)), Hall-effect measurement data are considered to be precise. All of the three samples were found to be n-type, which clearly indicates activation and n^+/p junction formation.

Mobility values of <60 cm^2/Vs suggest carrier concentration levels of ~10^{20} cm^{-3}. [8] SRP measurements on the 950 ºC Si sample presented in Fig. 3(a) also indicate n-type carrier existence at <35nm depth region but with a peak carrier concentration of $5x10^{19}$ cm^{-3}. The measurement error is large because the profile is too shallow for SRP. SRP data extracted R_s and carrier dose were 910 Ω/sq and $7.8x10^{13}$ cm^{-2}, inconsistent with the data in Fig. 2. We believe the true carrier concentration should be much larger than $5x10^{19}$ cm^{-3}.

We estimate maximum carrier concentration level (n_{max}) by two models. We assumed carrier concentration profile of $n(x) = \min(n_{max}, C_{SIMS}(x))$, and determine n_{max} that generates the measured (model A) R_s and (model B) carrier dose values in Fig. 2. The obtained n_{max} values are $1x10^{20}$ cm^{-3} (model A) and $2x10^{20}$ cm^{-3} (model B), respectively. The obtained carrier concentration values are summarized in Fig. 3(b) and support that the carrier concentration level of this 950 ºC Si sample is ~10^{20} cm^{-3}.

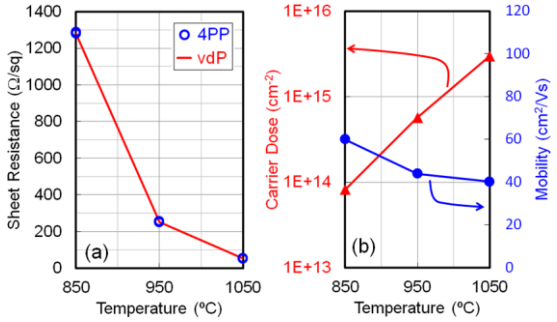
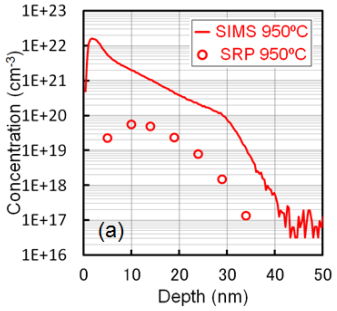


Fig. 2 (a) R_s and (b) carrier dose and mobility of As plasma doping into Si. Polarity of all the three samples is n-type.



(b)

Method	Carrier Conc. (cm^{-3})
Mobility	~10^{20}
SRP	5x10^{19}
Model A	1x10^{20}
Model B	2x10^{20}

Fig. 3 (a) SIMS/SRP profile for the 950 ºC Si sample. (b) Extracted carrier concentration for the 950 ºC Si sample from four different methods.

3.2 Germanium

Figure 4(a) shows sheet resistance reduction as increasing annealing temperature showing activation. However, in contrast to the silicon data in Fig. 2(a) there is roughly a 30% R_s discrepancy between 4PP and vdP due to non-negligible junction leakage for the Ge samples because Ge has lower bandgap (0.67eV) than Si (1.12eV). The Hall data was also magnetic field dependent. In this case, SRP is a better metrology tool for carrier activation evaluation for the Ge samples. SIMS/SRP profiles in Fig. 4(b) clearly indicate n-type carrier activation for the 750 ºC and 800 ºC Ge samples. Both the Ge samples have ~$10^{18}$$cm^{-3}$ carrier concentrations, consistent with the SIMS As dopant concentrations for 20-200nm depth range, which means 100% activation for the diffused region. Because diffusion depth is large for both the Ge samples unlike the silicon ones, we believe that SRP data is precise.

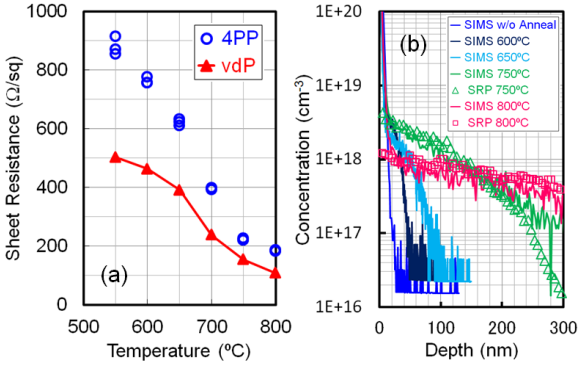


Fig. 4 (a) R_s and (b) SIMS/SRP profiles of As plasma doping into Ge. SRP indicates n-type carriers.

In order to compare ion implant and plasma doping mediated dopant transport, we modelled As depth profiles for the Ge samples using a Fick's Law model with fitting parameters (constant total dose and diffusion coefficient) matched to the SIMS data. Because the As concentration in the diffusion region is low enough to assume intrinsic diffusion, we assume the diffusion coefficient is independent of As concentration. Dopant transport in plasma doping is different from ion implantation because implanted ions being with them their own deep defects that mediate transport. It is also considerably different from solid state doping that relied on intrinsic defects and stress to mediate transport. Plasma doping is in between as only the near surface is disordered. Figure 5 shows the extracted diffusion coefficients and fitting results. Indeed, diffusion coefficients of plasma doping are significantly lower than those of ion implantation [5] and much closer to those of Ge-As alloy solid state doping [6]. That the diffusion coefficients for plasma doping are lower than for ion implantation is probably due differences in physical damage. PH_3 plasma doping of Ge would yield much shallower depth profile because diffusion coefficient of P into Ge is one order of magnitude lower than that of As into Ge (see Fig. 5(a)).

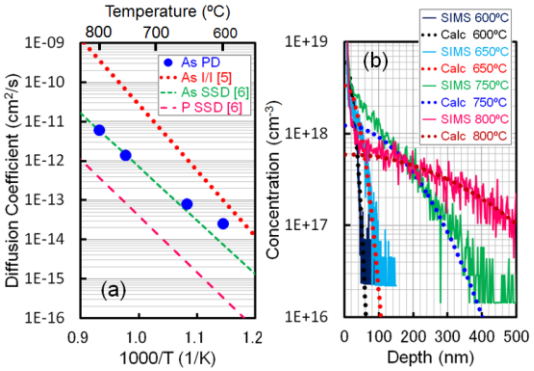


Fig. 5 (a) Calculated diffusion coefficient of anneal temperature for various doping methods; As plasma doping "As PD", As ion implantation "As I/I [5]" and As or P solid state doping "As SSD" and "P SSD" [6]. (b) SIMS and simulated depth profiles for the Ge samples.

4. Conclusions

We have demonstrated high carrier activation for the RLSA^{TM} plasma AsH_3 doping of Si and Ge using conventional rapid thermal annealing. The activation level is 10^{20} cm^{-3} and 10^{18} cm^{-3} for Si and Ge, respectively. Furthermore, the lack of physical damage from the RLSA^{TM} doping process lowers the intrinsic diffusion coefficient of As into Ge. This indicates process optimization can be used to engineer very high dose ultra-shallow junctions in Ge.

References [1] H. Ueda *et al.*, JAP **115** (2014) 214904. [2] T. Ueno *et al.*, SSDM (2012) PS-1-8. [3] H. Miyoshi *et al.*, JJAP **53** (2014) 04EA05. [4] H. Miyoshi *et al.*, VLSI (2014) T16.4. [5] C. O. Chui *et al.*, APL **83** (2003) p3275. [6] S. Brotzmann *et al.*, JAP **103** (2008) 033508. [7] A. Chroneosa, JAP **107** (2010) 076102. [8] G. Masetti *et al.*, IEEE ED **30** (1983) p764.