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Multiple implantation of $^{29}Si^+$ in semi-insulating GaAs and its characterisation

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Abstract. Formation of a uniform *n*-layer by multiple $^{29}Si^+$ implantation on LEC grown semi-insulating GaAs ⟨100⟩ substrate and its characterisation by differential Hall measurement at room temperature is reported. The implantation energies are 60, 160 and 260 keV with corresponding doses of 1×10^{12}, $2{\cdot}55 \times 10^{12}$ and $3 \times 10^{12}\,cm^{-2}$. As-implanted, uncapped substrates were furnace-annealed with face-to-face configuration in an N_2 ambient at 850°C with arsenic overpressure. After annealing, the samples were subjected to Hall measurements using Van der Pauw configuration. Experimental and theoretical (LSS) profiles are compared. Electrical activation of the dopant atoms was found to range from 65–90% with average mobility values lying between 2000–2300 $cm^2\,V^{-1}\,s^{-1}$. Uniform concentration of the *n*-layer $\sim 10^{17}\,cm^{-3}$ up to a depth of 0·3 μm has been achieved. These layers are used for the fabrication of power MESFETs.

Keywords. Multiple implantation; semi-insulating GaAs substrate; differential Hall measurement; van der Pauw configuration; secondary ion man spectroscopy.

1. Introduction

Formation of a uniform *n*-layer by implantation in GaAs substrates has now become an attractive technique for the fabrication of MMICs and discrete devices (Bujatti and Marcelje 1981; Asbeck *et al* 1983; Sakashita *et al* 1985; Shino *et al* 1985). The shape and depth of the implanted profile and the mobility are the main parameters affecting the ultimate device performance. To have a knowledge of the above, the present work of the characterization of *n* implanted layers has been undertaken. While SIMS (secondary ion mass spectroscopy) has been used to determine the as-implanted profiles of $^{29}Si^+$ into GaAs, much attention was generally given to the measurements of post-implantation annealed samples to determine the electrically activated profiles by differential Hall and differential capacitance–voltage (C–V) techniques at room temperature. Although the C–V technique is convenient for dopant depth profiling, there are some limitations. The shortest depth which can be probed is limited by the smallest depletion width and the maximum depth by the reverse bias which can be applied without excessive leakage. Differential Hall measurement, while it is destructive, can yield both the mobility value as well as the carrier concentration. In the present study we report the formation and characterisation of a uniform *n*-layer obtained by triple implantation of $^{29}Si^+$ in undoped semi-insulating GaAs.

2. Experimental

The substrates used in the present study were undoped semi-insulating ⟨100⟩ LEC grown crystals. Prior to implantation, the substrates were etched in $H_2O_2:H_2SO_4:H_2O$ (1 : 1 : 100) solution to have a fresh layer available for ion implantation. These substrates were then mounted with a 7° tilt to avoid channeling. $^{29}Si^+$ was implanted with energies of 60, 160, 260 keV at doses of 1×10^{12}, $2{\cdot}55 \times 10^{12}$ and 3×10^{12} cm^{-2} respectively. As-implanted substrates were then furnace-annealed in a face-to-face configuration at 850°C for 15 min in an N_2 ambient with arsenic overpressure (Kesahara *et al* 1979). Differential Hall measurements at room temperature in the dark were performed using van der Pauw configuration followed by chemical etching in the above-mentioned solution having an etch rate of 400 Å/min at 25°C. The differential C–V profiling technique was also used for depth profiling of the substrates.

3. Results and discussion

The quality of the substrate is of prime consideration for the fabrication of GaAs MESFETs and MMIC's by direct ion implantation. Good quality substrates contribute acceptor densities $N_A \sim 1\text{–}5 \times 10^{16}$ cm^{-3}. So, to get reproducible results, the GaAs substrates must be of high quality and their properties must remain unchanged during a thermal cycle upto 900°C in an N_2/Ar atmosphere for 30 min. This criterion is fulfilled with (i) the use of undoped SI LEC crystal grown from stoichiometric or slightly arsenic-rich melts so that [Ga]/[As] $\leqslant 1$, (ii) substrate resistivity $\geqslant 10^7$ ohm-cm or sheet resistance $\geqslant 10^9$ ohm/□, and (iii) measured mobility ~ 4500 cm^2/V.s (Thomas *et al* 1984).

To avoid channeling of the dopant ions along the lattice planes, it is necessary to make the dopant ions see the substrate as an amorphous material. This is achieved by tilting the substrate 7° from the normal to the ion beam. The dopant ions then follow the Gassian distribution according to LSS theory (Lindhard *et al* 1963) as given by

$$n(x) = \frac{N_s}{\sigma\sqrt{2\pi}} \exp\left[-\left(\frac{x - R_p}{\sigma\sqrt{2}}\right)^2\right], \tag{1}$$

where N_s, R_p and σ are the ion dose, mean projected range and the standard deviation respectively. The values of R_p and σ depend on the energy of dopant ions for a particular substrate. In the present case triple implantations were performed and the resultant distribution can be expressed as

$$N(x) = \sum_{i=1}^{3} \frac{N_{Si}}{\sigma_i\sqrt{2\pi}} \exp\left[-\left(\frac{x - R_{pi}}{\sigma_i\sqrt{2}}\right)^2\right]. \tag{2}$$

For the fabrication of GaAs MESFETs a uniform n layer with a carrier concentration of $\sim 1 \times 10^{17}$ cm^{-3} up to 0·2 μm is required. This can be achieved by multiple implantation with various energies and doses of the same ions. Post-implantation annealing of the substrate generally yields electrical activation (η) of the dopant ions to a varying degree. Expecting an average electrical activation of 50% we have chosen to fix the donor concentration n at $\sim 2 \times 10^{17}$ cm^{-3}. The energies were selected as 60, 160 and 260 keV with respective doses of 1×10^{12}, $2{\cdot}55 \times 10^{12}$ and 3×10^{12} cm^{-2}. The theoretical LSS curve for the above energies and doses is shown in figure 1.

The experimental electron concentration and mobility profiles were measured by the differential Hall technique at room temperature and are shown in figure 1 for two typical samples. It is observed that sample 25 shows a better electrical

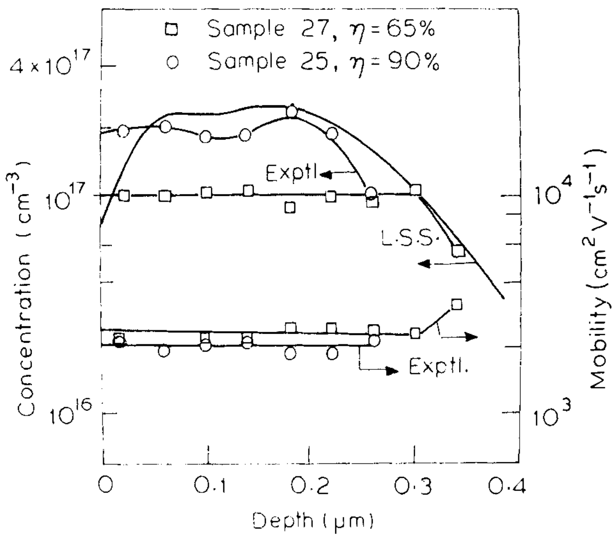

Figure 1. Electron concentration and mobility profiles obtained by differential Hall measurements at room temperature. The energies of $^{29}Si^+$ are 60, 160 and 260 keV with doses of 1×10^{12}, $2{\cdot}55 \times 10^{12}$ and $3 \times 10^{12}\ cm^{-2}$ respectively. The samples were thermally annealed at 850°C for 15 min in an N_2 ambient with As overpressure.

activation ($\eta = 90\%$) than that of sample 27 ($\eta = 65\%$). This variation in electrical activation may be caused by one or more of the following factors:

(i) deviation in original flatness of the polished surface,
(ii) unevenness of the surface created during pre-implantation etching,
(iii) warping due to heat treatment, and
(iv) presence of microscopic foreign particles while holding the substrate in the face-to-face configuration for annealing.

Although an appreciable variation in the value of η is observed, the electron mobility μ ranges between 2000 and 2300 $cm^2/V.s$. Since mobility depends on the crystal quality, the small change in μ observed in the present case may be due to their origin from the same batch material.

The characterization technique described above is destructive and time-consuming. For a quick qualitative estimation of the carrier concentration, the substrates were subjected to non-destructive testing of breakdown voltage measurements. Almost all the samples showed a breakdown voltage in the range of 11–12 V at 10 μA implying an n concentration of the level of $\sim 10^{17}\ cm^{-3}$.

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