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# CHARACTERISTICS OF POLYCRYSTALLINE FILMS GROWN BY ULTRAHIGH VACUUM CHEMICAL VAPOR DEPOSITION SYSTEM

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**Abstract**—*In situ* boron-doped polycrystalline $Si_{1-x}Ge_x$ (poly-$Si_{1-x}Ge_x$) films deposited by ultrahigh vacuum chemical vapor deposition (UHV/CVD) system were characterized. Optimum fitted values of grain boundary trap state densities, $4.0 \times 10^{12}\,cm^{-2}$ and $4.9 \times 10^{12}\,cm^{-2}$ were obtained for poly-Si and poly-$Si_{0.79}Ge_{0.21}$, respectively. The extracted average carrier concentration in the grain agrees with secondary ion mass spectroscopy (SIMS) analysis. In turn, we found that these films are suitable Hall elements to sense magnetic field. Experimental results show that the sensitivity decreased with the increasing input current, which can be well explained using the thermionic emission theory. Finally, we use these films to fabricate thin film transistors.

## 1. INTRODUCTION

Polycrystalline Si and $Si_{1-x}Ge_x$ (poly-Si and poly-$Si_{1-x}Ge_x$) thin films deposited on $SiO_2$ surfaces are important materials for microelectronic manufacturation. For some specific applications, such as the thin film transistors (TFTs) made on glasses, a low-temperature deposition technique is desired. Recently, we have shown that the ultrahigh vacuum chemical vapor deposition (UHV/CVD) can meet such a requirement[1]. This approach deposits poly-Si and poly-$Si_{1-x}Ge_x$ films at reduced pressures (e.g. 1–2 mtorr), which is low compared to that of conventional low pressure chemical vapor deposition (LPCVD) (normally $>100$ mtorr) and leads to fine-grain growth below 550°C without employing further annealing treatments. Utilizing this technique, we have developed a novel process to fabricate poly-Si or poly-$Si_{1-x}Ge_x$ TFTs[1]. In order to realize these devices for practical usage, more detailed understanding of the material properties associated with these deposited films is needed. In this study, we examined and characterized these materials using Hall measurement associated with their application for sensing magnetic field and the completed TFT performance.

Poly-Si and poly-$Si_{1-x}Ge_x$ are different from crystalline silicon and crystalline silicon–germanium due to their inhomogeneous properties and there exist many trapping sources in the grain boundary. In this work, we propose a simple resistive-network model[2–4] to fit the magnetic sensitivity. In order to calculate the magnetic sensitivity of polycrystalline films we must know all pertinent parameters. The grain size is an important parameter in this fitting work. From plan view transmission electron microscope (TEM) micrographs, we can determine the average grain size by following formula[5]:

$$L_G = 1.5\frac{l}{mn_g}, \tag{1}$$

where 1.5 is the correction factor, $l$ is the interception length across the micrograph, $m$ is the micrograph magnification, and $n_g$ is the number of grains between $l$. Except the grain size the grain boundary trap state density, $N_t$, is also an important factor which relates to the film quality (the lower $N_t$, the higher quality).

## 2. EXPERIMENTS

In this work, *in situ* boron-doped poly-Si and poly-$Si_{1-x}Ge_x$ films were deposited at 550°C on 3 in. Si wafers coated with thermal oxide. Pure $SiH_4$ and 10% $GeH_4$ in $H_2$ were used as the depositing source. 1% $B_2H_6$ and 100 ppm $B_2H_6$ in $H_2$ were used as the doping gases. The $SiH_4$ flow rate was kept at 20 sccm throughout the deposition. On the other hand, the $GeH_4$ flow rate was kept at 9 sccm for poly-$Si_{1-x}Ge_x$ deposition. Prior to deposition the wafer was cleaned in a solution of $H_2SO_4/H_2O_2$(3:1) for 15 min, followed by a 5 min. rinse in deionized (D.I.) water, and then spun dry with $N_2$ gas. Film thicknesses were measured using a Dektak 3030 surface profile measuring system. They are 1800–2100 Å and 1400–1500 Å for poly-Si and poly-$Si_{1-x}Ge_x$, respectively.

The test samples were defined by a photomask and etched in an ambient mixture of 5 sccm $O_2$ and 40 sccm $CF_4$ gases by reactive ion etching (RIE) system. The Ge content $x$ of the poly-$Si_{1-x}Ge_x$ films was determined by Rutherford backscattering spectroscopy (RBS). It is 0.21 for this work. After defining the sample, a 4000 Å plasma-enhanced chemical vapor deposition (PECVD) oxide was capped. The contact holes were etched by way of dipping the sample into BOE then a 5000 Å aluminum pattern was formed. Finally, the sample was sintered at 400°C for 30 min to guarantee the good contact characteristics.

Prior to this work, carrier concentrations and mobilities had been measured by van der Pauw–Hall measurement and resistivities were measured by four-point probe. A HP4145 semiconductor parameter analyzer had been used to measure the current–voltage ($I$–$V$) curve to check whether a good contact characteristic exists. Linear $I$–$V$ curves are due to the applied voltage drop in every grain is much less than thermal potential, $kT$. However, as the voltage drop is compatible or greater than $kT$, the nonlinear relation would appear. After finishing the $I$–$V$ curve measurement, the same sample was cut and wire-bonded on the testing bat for Hall voltage measurement. The Gaussmeter was used to calibrate the magnetic fields in variety of ranges (0–10,000 Gauss). A Keithley 220 programmable current source offers the input current. A Keithley 485 autoranging pico-ammeter to check the output current. If the output current deviates from the input current more than 1%, we will give up the measurement and prepare another sample. A Keithley 196 system DMM to measure the Hall voltage to the accuracy, 0.1 $\mu$V. Taking current as the measuring parameter and changing the magnetic field from 0 to 10,000 Gauss to obtain the corresponding readout Hall voltage.

We use the bottom-gate poly-$Si_{1-x}Ge_x$ TFTs to extract the trapping density. The measurement is according to the method proposed by Levinson *et al.* [6]. And the main process steps of TFTs are illustrated in our prior work[7].

## 3. RESULTS AND DISCUSSION

In this work, we assumed that the grain with the same grain size has the same grain boundary trap state density. In plan view TEM micrographs, we found the grain size can be divided into two regions for simplicity. Each region has about the same grain size. For poly-Si, dopant concentrations below $2.41 \times 10^{19}\,cm^{-3}$ and above the dopant concentration have the grain sizes about 830 and 630 Å, respectively. For poly-$Si_{1-x}Ge_x$, dopant concentrations below $2.57 \times 10^{19}\,cm^{-3}$ and above the dopant concentration have the grain sizes about 1920 and 830 Å, respectively. We choose these lowest five dopant concentrations, which have grain sizes about 830 Å and 1920 Å, for both poly-Si and poly-$Si_{1-x}Ge_x$, respectively, to start our fitting work.

### *3.1. Grain boundary trap state density and pertinent parameters*

The grain boundary trap state density, $N_t$, is a fitting parameter. We considered a lower trap state density and gave a value of $N_t$ by guess for this fitting then obtained the actual average concentration, $n_1$. Then to calculate the Hall voltage which compared with experimental data. If these calculated Hall voltages are reasonable agreement to each measured results, the given $N_t$ is really corresponding to all dopant concentrations with the same grain size then the fitting is completed and the value of $N_t$ was obtained. Otherwise, we will guess another value of $N_t$ to repeat the fitting until the work is finished. By way of the fitting, we obtain the grain boundary trap density and actual average concentration in the grain additionally. The optimum values of $N_t$ are $4.0 \times 10^{12}\,cm^{-2}$ and $4.9 \times 10^{12}\,cm^{-2}$ for poly-Si and poly-$Si_{1-x}Ge_x$, respectively. After this fitting, we analyzed the SIMS data and found that below some dopant concentration the actual average carrier concentration, $n_1$, agrees with the boron concentration, indicating that these films are all nearly fully activated (i.e. $n_1$ is equal to the boron concentration) as shown in Figs 1(a) and (b). Since these films are fully activated, we can use these measured results and the grain boundary trapping model[8–10]:

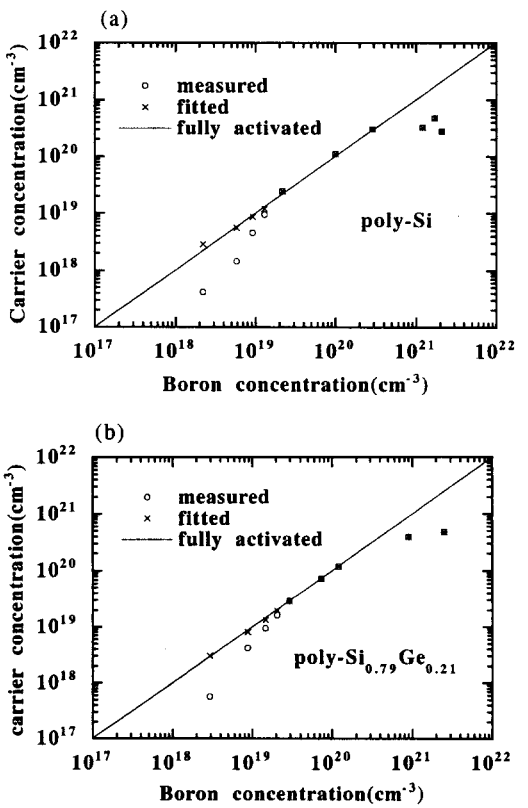


Fig. 1. The relationship of the activated carrier concentration vs boron concentration for: (a) poly-Si; and (b) poly-$Si_{0.79}Ge_{0.21}$.

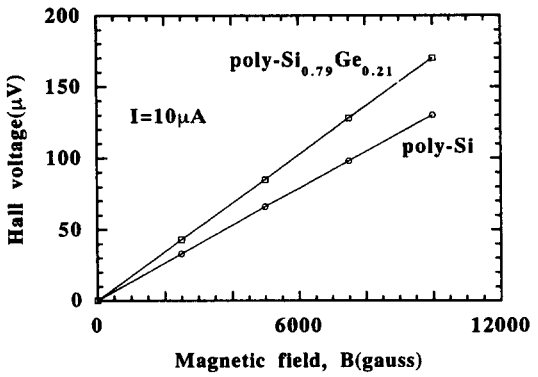


Fig. 2. The relationship of the Hall voltage and magnetic field at low current.

$$\rho = \frac{kT}{q^2 n_1 v_c L_G} \exp\left(\frac{qV_B}{kT}\right). \quad (2)$$

From this data, the grain boundary trap state density, $N_t$, was determined. They are $4.7 \times 10^{12}\,\mathrm{cm}^{-2}$ and $6.4 \times 10^{12}\,\mathrm{cm}^{-2}$ for poly-Si and poly-$Si_{1-x}Ge_x$, respectively. These values are reasonable agreement to our fitting results implies that the resistive-network model can well explain the Hall voltage in poly-Si and poly-$Si_{1-x}Ge_x$ films. On the other hand, prior to this fitting work we had assumed that the grain boundary trap state density is not too high and there are the same trap state density with the same grain size. Obviously, checking the fitting result we can find they don't conflict with our primary assumption. The obtained critical dopant concentrations[8–10] are $5.6 \times 10^{17}\,\mathrm{cm}^{-3}$ and $3.3 \times 10^{17}\,\mathrm{cm}^{-3}$ for poly-Si and poly-$Si_{1-x}Ge_x$, respectively.

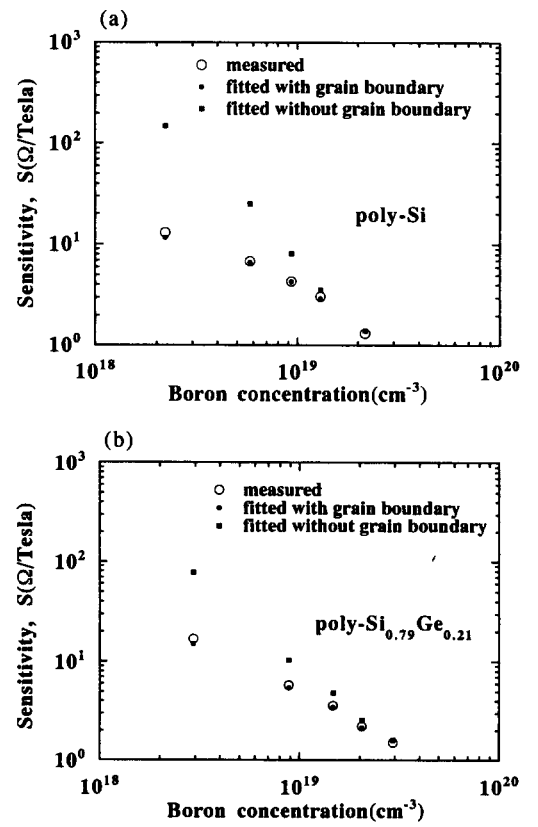


Fig. 3. The sensitivity vs boron concentration plot for: (a) poly-Si; and (b) poly-$Si_{0.79}Ge_{0.21}$.

### 3.2. *Hall voltages and the sensitivity lowering*

Heavily doped crystalline silicon films were used as Hall elements to sense magnetic field even though the sensitivity is low[11]. In this work, we use poly-Si and poly-$Si_{1-x}Ge_x$ films as Hall elements. The $V_H$ vs $B$ curve is shown in Fig. 2. The linear relationship between $V_H$ and wide range $B$ (0–10,000 Gauss) implies that these polycrystalline films are suitable Hall elements. In order to estimate the application for magnetic field sensors, the sensitivity can be defined as[11]:

$$S = \frac{V_H}{IB}. \quad (3)$$

Figures 3(a) and (b) are the sensitivities for a variety of dopant concentrations at low input current. In heavily doped samples, we can neglect the grain boundary with homogeneous properties. At the lightly dopant concentration, the calculated result deviates much from experimental data due to the increasing barrier height at grain boundary. Using the resistive-network model with Bennett's theory[12] we can estimate the Hall voltage quantitatively.

According to the definition in eqn (3), we found that the sensitivity is in the useful range [see Figs 3(a) and (b)] and will decrease with increasing dopant concentration. Therefore, we need to use the polycrystalline films with low doping concentration to obtain the high sensitivity. However, the sensitivity in which low doping films will decrease with increasing input current. This phenomenum is due to that the voltage drop across per grain is compatible or greater than the thermal potential, $kT$, with high input current. To consider the current transport in two directions across the grain boundary, the net current $I$ can be expressed as following[10]:

$$I = I_0 \sinh\left(\frac{qV_g}{2kT}\right), \quad (4)$$

and the sensitivity can be derived as:

$$S = \frac{V_H}{IB} = S_0\left[\sinh\left(\frac{qV_g}{2kT}\right)\right]^{-1} \quad \text{and} \quad S_0 = S(I \to 0) \quad (5)$$

Figures 4(a) and (b) represent the $S$–$I$ curve according to eqn (5) compared with experimental data. The sensitivity decreasing is more evident at low doped films, which is attributed to the higher barrier. The voltage drop in lower doped films on each grain is larger than the heavily doped ones.

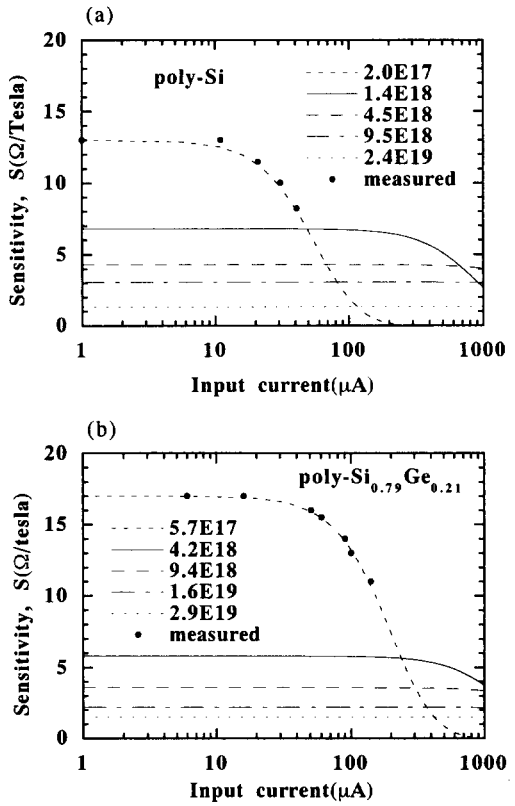


Fig. 4. The relationship of the sensitivity and input current for: (a) poly-Si; and (b) poly-$Si_{0.79}Ge_{0.21}$ in a variety of dopant concentrations.

### *3.3. From TFT characteristics to extract the trap state density*

The larger amount of trapping states contained in the grain boundaries is essential in influencing the electrical characteristics of poly-$Si_{1-x}Ge_x$ films and make the conduction behavior of polycrystalline TFTs significantly different from that of Si/or $Si_{1-x}Ge_x$ MOSFETs[13]. It is shown previously that the carrier-trapping model[8,9] is a simple but efficient way of describing the conduction behavior of carriers in polycrystalline materials. The potential barrier created by the trapping states is related to the difference in carrier concentration between the grain and the grain boundary. For TFT operation, the variation of the gate voltage would allow to modulate the carrier concentration inside the conduction channel and, thus, the barrier height at grain boundaries. Based on this consideration, the amount of trapping state density, $N_t$, is possible to be extracted from the current–voltage characteristics of TFTs. This work is done by Levinson *et al.*[6]. Using their derivative, we can estimate the value of $N_t$ from the $\ln[I_{ds}/(V_g - V_{FB})]$ vs $(V_g - V_{FB})^{-2}$ characteristics. The results are shown in Fig. 5 and detailed in Table 1. As can be seen in Table 1 that the addition of Ge atoms would introduce a considerable amount of $N_t$, implying that the Ge incorporation in these polycrystalline films would degrade the film quality.

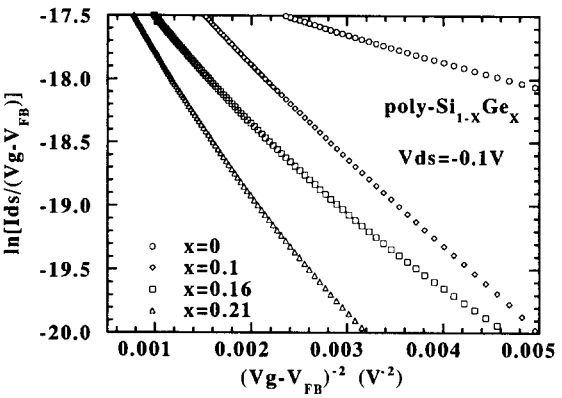


Fig. 5. Plot of $\ln[I_{ds}/(V_g - V_{FB})]$ vs $(V_g - V_{FB})^{-2}$ was used to determine the value of $N_t$.

Table 1. The grain boundary trap state density, $N_t$ of polycrystalline films

| Ge content $x$ (at. %) | 0 | 10 | 16 | 21 |
|---|---|---|---|---|
| $N_t$ ($\times 10^{12}$ cm$^{-2}$) | | | | |
| By $I_{ds}$ vs $V_g$ | 5.30 | 9.80 | 10.7 | 12.6 |
| By $\ln(\rho n_1)$ vs $1/n_1$ | 4.7 | — | — | 6.4 |
| By this work | 4.0 | — | — | 4.9 |

## 4. CONCLUSIONS

By way of *in situ* boron doping technique, we obtained as deposited polycrystalline films with effective carrier concentrations in the range of $10^{17}$–$10^{20}$ cm$^{-3}$ for both poly-Si and poly-$Si_{1-x}Ge_x$. In turn, we have fitted the Hall voltage in these films without measuring the barrier height between grain boundaries and can well explain the measured results. By this fitting work, we can also obtain the grain boundary trap state density and actual average carrier concentration in the grain. Comparing these carrier concentrations with SIMS analysis, we found that these films are nearly fully activated up to a particular concentration. Under the fully activated condition, we can also extract the grain boundary trap state density from the slope of $\ln(\rho n_1)$ vs $1/n_1$ plot according to the grain boundary trapping model. These grain boundary trap state densities are all lower than in LPCVD grown films, which indicates the quality of these UHV/CVD grown films without any post-treatment are extremely high. We found that these films are useful Hall elements for sensing magnetic fields due to the wide range linear relationship between the Hall voltage and magnetic field.

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