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RESEARCH ARTICLE

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Electrochemical capacitance-voltage characterization of plasma-doped ultra-shallow junctions

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Abstract Ultra-shallow Si p^+n junctions formed by plasma doping are characterized by electrochemical capacitance-voltage (ECV). By comparing ECV results with those of secondary ion mass spectroscopy (SIMS), it is found that the dopant concentration profiles in heavily-doped p^+ layer as well as junction depths measured by ECV are in good agreement with those measured by SIMS. However, the ECV measurement of dopant concentration in the underlying lightly doped n-type substrate is significantly influenced by the upper heavily-doped layer. The ECV technique is also easy to control and reproduce. The ECV results of ultra-shallow junctions (USJ) formed by plasma doping followed by different annealing processes show that ECV is capable of reliably characterizing a Si USJ with junction depth as low as 10 nm, and dopant concentration up to 10^{21} cm^{-3}. Also, its depth resolution can be as fine as 1 nm. Therefore, it shows great potential in application for characterizing USJ in the sub-65 nm technology node CMOS devices.

Keywords electrochemical capacitance-voltage, ultra-shallow junction, dopant concentration

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1 Introduction

As device dimensions shrink continuously, the formation and characterization of ultra-shallow junctions (USJ) become crucial for future device fabrication. According to the 2005 International Technology Roadmap for Semiconductors, the MOS device junction depth of the contact field in source and drain will decrease to 27.5 and 19.8 nm as device dimension is scaled down to the sub-65 nm and sub-45 nm technology nodes (http://www.itrs.net/Links/2005ITRS/Home2005.htm). To form such ultra-shallow junctions, novel doping methods such as plasma doping [1], gas doping and solid doping, are studied apart from low energy ion implantation. New annealing techniques such as flash annealing [2] and laser annealing [3] are being developed. Besides sheet resistance, dopant concentration also plays a very important role in device characteristics. Concentration gradient of the source/drain region at the gate edge, i.e., lightly doped drain or drain extension will control short channel effects and hot carrier effects. The electrical behaviors of a device are eventually correlated tightly to electrical concentration. Therefore, it is very important to measure the activated doping level and its distribution in a semiconductor.

Many techniques exist currently for dopant profiling, including spreading resistance profiling (SRP), capacitance-voltage (C-V) profiling, secondary ion mass spectroscopy (SIMS), differential Hall effect (DHE) profiling and electrochemical capacitance-voltage (ECV) profiling [4–8]. Each has its own respective advantages and disadvantages. As can be easily conducted in experiments and consisting of good resolution and accuracy, C-V profiling has limited profiling capability of high dopant concentration and high depth due to breakdown at reverse bias. SRP does not suffer from such depth limitation and is capable of profiling through junctions, but the technique requires elaborative sample preparation, probe conditioning and calibration procedures. Furthermore, the profile depends on the choice of the correction factor algorithm and assumed bulk mobility

[9–11]. Because of the limit of grind angle and probe radius, it is difficult to characterize ultra-shallow junctions. SIMS features good resolution and accuracy, but it requires rather complex and expensive instrumentation and it also gives concentration chemical rather than electrical. C-V measuring and etching can be done by ECV by virtue of semiconductor/electrolyte Schottky interface. Profiles of electrical concentration can be measured by repeatedly etching and measuring. ECV also does not suffer from a depth limitation, but sometimes inaccurate definition of the etched depth and etched area has detrimental influence on the results. Moreover, ECV is well-established for III-V compound semiconductor profiling [8], but only a few applications on Si have been reported [12–14].

In this work, the ECV technique has been employed to characterize USJ of depths down to 10–30 nm formed by plasma doping (PD). The results are compared with those of SIMS.

2 Experiments

The USJ p^+n junction samples utilized in this work were prepared by plasma doping. Spike annealing and flash lamp annealing were performed. Sample 1 is from spike annealing and samples 2 and 3 are from flash lamp annealing. The sample process conditions are listed in Table 1.

The ECV equipment used in this work is the PN4300 (Bio-Rad). There are four electrodes in the equipment, i. e., carbon (counter) electrode, platinum electrode, saturated calomel electrode and semiconductor working electrode. C-V measurement of the semiconductor/electrolyte interface Schottky junction can be done by dropping the voltage between the platinum electrode and semiconductor working electrode. Etching can occur by dropping the voltage between the carbon electrode and semiconductor working electrode. The saturated calomel electrode is used as a reference in the voltage measurement. There is a window from which light can illuminate the semiconductor. N-type semiconductor can be etched by illuminating and p-type semiconductor can be etched without illuminating. The C-V measurement and semiconductor etching are controlled by a computer. The details of the equipment can be found in Ref. [8]. The electrolyte used in this work is NaF/H_2SO_4 solution [15].

3 Results and discussion

Figure 1 shows SIMS and ECV profiling of p^+n junction (Sample #1) formed by PD. The dopant concentration profiles at three different positions of the sample (diameter of measuring area about 1 mm) are shown in Fig. 1. It shows that the sample is p-type at 0-25 nm depth and its surface concentration is 10^{21} cm^{-3}. Dopant concentration decreases when the depth increases. When the depth goes beyond 35 nm, the semiconductor shows to be doped n-type, and the concentration is almost constant. Within the range of 25–35 nm the dopant type and concentration are uncertain. The results show that the sample is a p^+n junction and its junction depth is about 25–35 nm. Dopant concentration near the junction cannot be measured because of carrier depletion effect. The data obtained at three positions are essentially the same within the depth range of 0–10 nm. Though the data are scattered in the depth range of 10–25 nm, they are located in a line, indicating that the sample is quite homogeneous and the measurement is reliable. SIMS results of this sample are also shown in Fig. 1, where it can be seen that the SIMS results and ECV results are essentially the same within the depth range of 2–10 nm (SIMS results are not reliable in the region very close to the surface). Dopant concentration measured by ECV is lower than that by SIMS in the depth range of 10–25 nm. The reason is that the ECV measurement near the junction is affected by the carrier depletion effect. From the SIMS junction depth definition (where the dopant concentration is 10^{18} cm^{-3}) we know that the junction of the sample is about 29 nm. It is the same as the result from ECV. The substrate doping concentration measured from p^+n junction is 10^{18} cm^{-3}. However, the concentration measured from the bare n-type substrate is 3×10^{15} cm^{-3}. In other words, the substrate doping concentration measured from the p^+n junction is two or three orders higher than the real one. This is reasonable when the difference between the etched and contact areas is taken into account.

Figure 2 is the diagram of electrolyte/semiconductor contact in ECV measurement. The diagram shows the difference between the contact area and etched area. Generally, the contact area may be a little bit larger than the etched area, indicating that the dopant concentration at deep position may be affected by the top layer, especially when the top layer has high dopant concentration. The Schottky contact on the residual top p^+ layer

Table 1 Process conditions for the plasma doping samples

sample No.	dose /cm^{-2}	Rs /Ω·sq.$^{-1}$	annealing condition	annealing temperature/°C
1	2.3E+14	1050	spike annealing	1075
2	9.2E+14	1000	flash lamp annealing	1287
3	2.4E+15	530	flash lamp annealing	1295

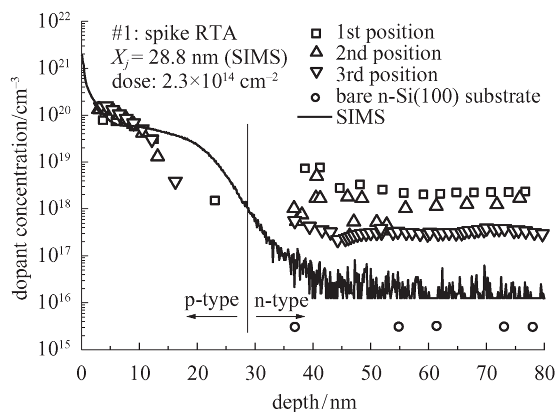


Fig. 1 ECV profiling of a p⁺n junction formed by PD

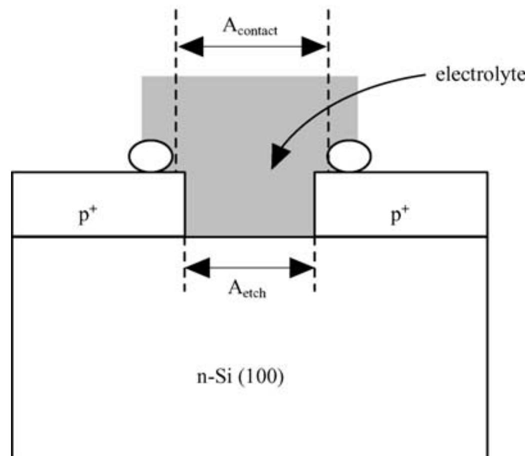
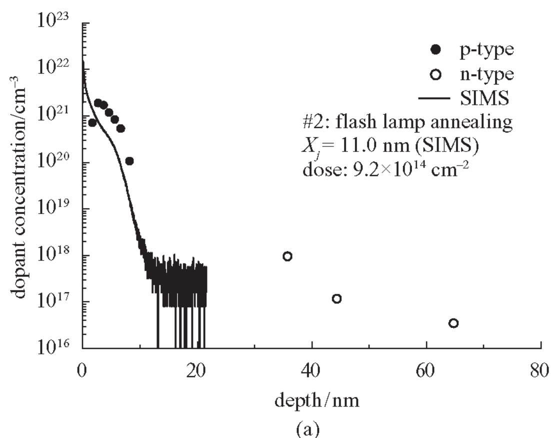


Fig. 2 Diagram of electrolyte/semiconductor contact in ECV measurement
Note: The difference between etched and contact areas is shown

results in very small depletion and in consequence very large zero-bias capacitance, though the area is small. The capacitance of the un-etched top layer connects in parallel with the capacitance of the n-type substrate. When the ECV measurement of p⁺n junctions reaches n-type substrate, the capacitance may be much bigger than that solely on the n-type substrate. As a result, the measured substrate doping concentration may be higher than the real one. Because the difference between the etched and contact areas is uncertain, the deviation of the substrate doping concentration is subsequently uncertain. If the top-layer has high concentration, the top-layer effect will increase the dopant concentration in deep depth significantly and sometimes even invert the sign of the $\mathrm{d}C/\mathrm{d}V$, thus predicting wrong dopant type.

Figures 3 (a)-(b) show SIMS and ECV profiling of p⁺n junction samples (#2, #3) formed by PD. The dopant profile measured by ECV is smooth, indicating that ECV etching and C-V measurement are very reliable. Since the shape of the profiling is reasonable, it can be concluded that the results are credible. At the surface region with high doping concentration, the measurement step is about 1 nm. Also, the dopant type is inverted at a depth of 10–20 nm. Results show that ECV is capable of characterizing a Si USJ with junction depth as low as 10 nm, and its depth resolution can be as fine as 1 nm. The concentration measured by ECV is higher than that derived by SIMS. The discrepancy may come from the difference between the etched and contact areas, measurement frequency, and the choice of series and parallel models [16]. The dopant concentration of the p⁺ layer of those samples is mostly in the range of 10^{20}–10^{21} cm^{-3}, and some concentration peaks exceed 10^{22} cm^{-3}, which is related to the reason mentioned above that the dopant concentration measured by ECV may be higher. It is worth noting that with such high concentration, the Schottky contact can still be formed without the penalty of too much leakage. It is due to the fact that the C-V measurement in ECV is done with almost zero bias. The dopant concentration profiling at a deep region by ECV



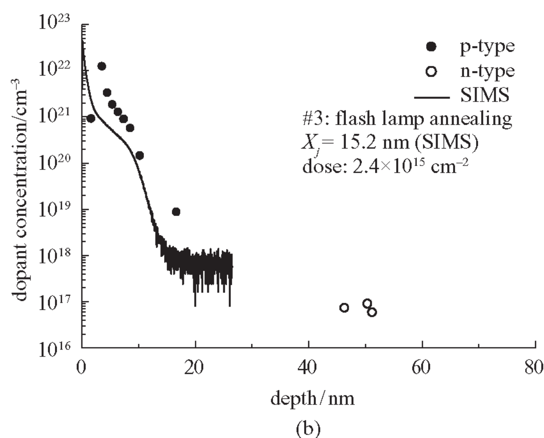


Fig. 3 Dopant concentration profiles measured by ECV for ultra-shallow p⁺n junctions formed by plasma doping followed by flash annealing. (a) sample #2; (b) sample #3

is realized by electrochemical etching rather than by the increase of reverse bias voltage. The leakage current can be so small, though the dopant concentration is high.

Since the concentration measured by ECV is electrical, it should have more direct relation with device characteristics. On the other hand, with SIMS data, ECV can be used to study dopant activation rate as well as its process dependence. The junction depths (X_j) determined by ECV and by SIMS are listed in Table 2. The values of X_j determined by ECV are in good agreement with those determined by SIMS.

Table 2 Junction depth measured by SIMS/ECV for plasma doped samples

sample No.	X_j/nm by SMIS	X_j/nm by ECV
1	28.8	29
2	11.0	8
3	15.2	17

4 Conclusions

The USJ formed by PD has been successfully characterized by ECV. Results show that ECV is capable of characterizing the p^+n junction with a junction depth of 10 nm, and the junction depth determined by ECV is in good agreement with that determined by SIMS. ECV has good concentration profiling capability, especially for the top layer. Dopant concentration up to 10^{21} cm^{-3} can be measured. Also, the depth resolution can be as fine as 1 nm. Therefore, it shows great potential in application for characterizing USJ in sub-65 nm CMOS devices.

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