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Proton-irradiation technology for high-frequency high-current silicon welding diode manufacturing

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Abstract. Different proton irradiation regimes were tested to provide more than 20 kHz-frequency, soft reverse recovery "snap-less" behavior, low forward voltage drop and leakage current for 50 mm diameter 7 kA/400 V welding diode Al/Si/Mo structure. Silicon diode with such parameters is very suitable for high frequency resistance welding machines of new generation for robotic welding.

1. Introduction

Resistance welding is a technique used mainly for joining sheets of metal. In comparison with other welding methods, resistance welding is very efficient, as it causes little pollution and limited work piece deformation. It has high production rates, can easily be automated and requires no filler materials. Modern high power welding machinery requires diodes able to manage very high current levels in order to reduce the number of paralleled devices and to properly work with increased frequency. It is used extensively in the automotive industry since most cars have several thousand of spot welds made by industrial robots. Each welding cycle represents a load cycle for the diodes and the expected lifetime is generally more than ten million cycles. To keep the temperature swing as low as possible during the cycle, the diodes must be designed for very good trade-off between static and dynamic characteristics, lowest possible losses and thermal impedance [1, 2].

The main fundamental parameter that determines rectifier diode frequency except its geometry and doping levels is the minor charge carrier lifetime in active regions and its spatial distribution [3–6]. The lifetime value depends on characteristics of recombination centres in semiconductors, such as energy level in the forbidden zone, electrons and holes capture cross sections and concentration [7, 8].

Welding diode has the thinnest and lowest resistance base among deep-diffused high current silicon diodes, that is why accelerator-based [9–11] electron beam technology is efficient for frequency increasing from common 1–2 kHz to 10–12 kHz [12, 13]. However, further frequency increase by this method is limited by growth of the forward voltage drop, leakage current and not soft behavior during reverse recovery due to uniform distribution of recombination centres in the base region. Because of good previous results for high voltage diodes [14, 15] different proton treatments were tested in this work to achieve the desired 20–25 kHz frequency and high softness factor for welding diode. This aim is caused by the fact that the 20 kHz inverter (now transistor-based) technology shows numerous advantages. So the residual ripple of the welding current is negligible. The short current rise times enable extremely short welding operations of only several milliseconds without any flashes. The control cycle time of 25 µs ensures uniform and reproducible quality in the welded joint, even at these short welding times. The areas of application are projection welding and the welding of materials which possess good electrical conductivity, e.g. aluminum or copper. As a result of the high inverter frequency of 20 kHz, the welding transformers are working almost quietly. Welding diode should have reverse recovery time about 1.0–1.5 µs to meet these requirements surely.

2. Samples and Proton Irradiation Equipment

2.1. Welding diode samples
Welding diode structures of two types were involved into experimental investigations. First structures (Al/n^+np^+-Si/Al/Mo) were joined with Mo thermo-compensator via Al under high (about 800 °C) temperature and pressure. Second structures (Al/ p^+nn^+-Si/nano-Ag/Mo) were joined with Mo thermo-compensator via nano-Ag sintering paste using lower (about 250 °C) temperature. Both 50 mm diameter silicon diode structures (7 kA, 400 V) were formed identically using the same deep-diffusion process and electron-beam evaporation for 7 µm thick Al top contact making. Specific diode structure parameters are: 85–90 µm gradually Al- and B-doped p^+-anode; 50 µm uniformly P-doped (8–10 Ohm·cm initial substrate) n-base and 60 µm gradually P-doped n^+-cathode contact region.

2.2. Proton irradiation equipment
Two different accelerators were used for irradiation: pulsed 25 MeV proton linac I-2 in ITEP [16] and 3 MV tandem accelerator Tandetron 4130 in IPPE. The irradiation scheme is shown in figure 1.

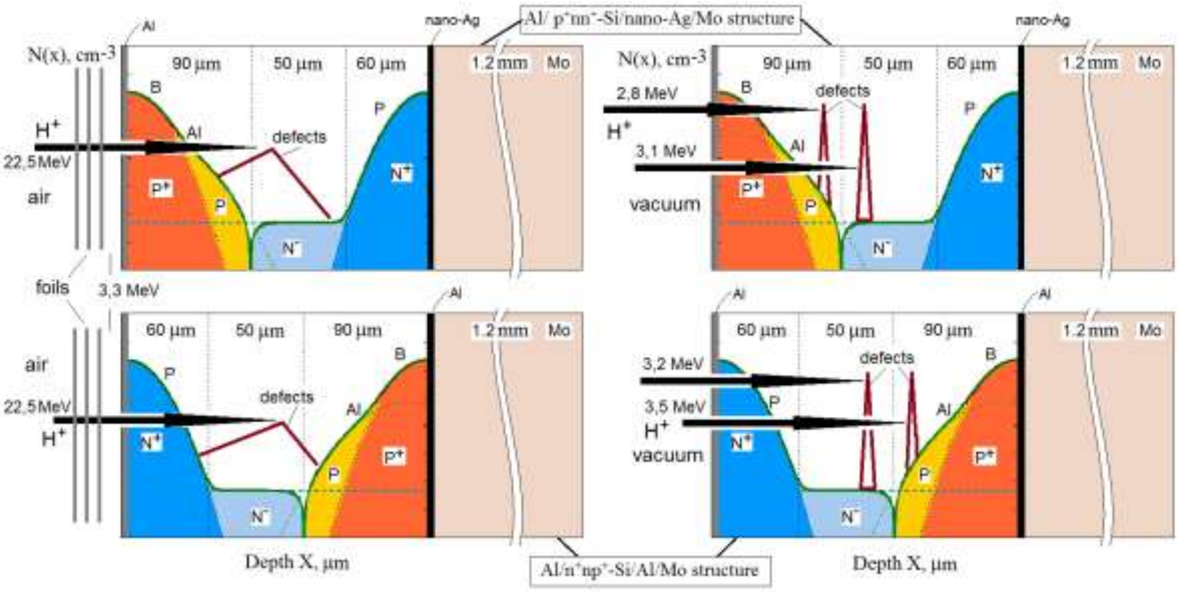

Figure 1. Schemes and variety of proton irradiation experiments.

Linac I-2 accelerates protons with fixed energy of 24.6 MeV and initial average current of 5 µA. Such high proton energy gives an opportunity to output the beam on air throw relatively thick and robust Al-window with low energy losses in it and without risks of its destruction or burning through during irradiation. After the window, protons have energy of 22.5 MeV and lower input energy needed on sample surface is achieved by using different stopping foils. Longitudinal straggle calculated using SRIM-2008 is about 55 µm in silicon for such irradiation conditions through Al-foils, and defects concentration decreases smoothly from the peak in the base near the junction towards the cathode region. In this case, welding diode structures were irradiated with energy of 3.3 MeV with fluencies $\Phi_{H+}=10^{11}\ldots10^{12}$ cm^{-2}. Measurements of electrical parameters (Q_{rr} is reverse recovery charge, t_{rr} is reverse recovery time at dI/dt=100 A/μs and forward current of 1 kA, S is softness factor, I_{DRM} is leakage current at reverse voltage of 400 V and 150 °C, V_{FM} is forward voltage drop at forward current of 5 kA) using the DBC-226 measurement system were realized after thermal annealing (240 ºC, 3 hours) of irradiated diode structures. Oriented optimum proton fluence of $4\cdot10^{11}$ cm^{-2} was determined.

Tandetron 4130 accelerates protons with any energy in the range from 0.2 to 6.6 MeV with precise 0.1% adjustment and small proton and defects struggling (about some microns). In this case, irradiation experiments were carried out in a vacuum chamber with two different energies of 3.2 and 3.5 MeV (first type structures) and 2.8 and 3.1 MeV (second type structures) to form two defect peaks around and near the p^+n-junction [17] under fluence of $2\cdot10^{11}$ cm^{-2} for each energy. Irradiated diode structures also were annealed at the same conditions and then measured.

3. Experimental results

Essential experimental results are summarized in the table 1.

Table 1. Electrical parameters of proton irradiated welding diode structures

Diode type	E_{H+}, MeV	Straggle, мm	Q_{rr}, мC	t_{rr}, мs	S, a.u.	I_{DRM}, mA	V_{FM}, V
1	3.3	55	NA	1.2–1.3	0.4–0.6	15–20	1.2–1.3
1	3.2; 3.5	2–3	8–10	1.3–1.5	0.7–1.0	6–10	1.1–1.2
2	3.3	55	19–20	1.1–1.5	0.6–1.1	8–12	1.2–1.3
2	2.8; 3.1	2–3	7–9	1.0–1.4	1.5–4.6	0.2–2	1.1–1.2

Thus, all tested proton irradiation treatment could be applied for softness factor increasing from initial values of 0.2–0.4, but with different efficiency and influences on other characteristics. Silver sintered Al/p^+nn^+-Si/nano-Ag/Mo structures show better results for both irradiation techniques because protons do not cross the diode base region. Defects in the base body decrease the softness factor. Narrow straggle irradiation shows better results for both types of structures because of more local defect formation near the junction especially for Al/p^+nn^+-Si/nano-Ag/Mo structures that demonstrate the best electrical parameters. Nevertheless, cost-effective high volume proton treatment of bipolar device structures in vacuum needs energy efficient very reliable RFQ-accelerator similar to that described in [18] with wide treatment area up to 200x200 mm and equipped with high-performance high-volume vacuum automated chamber.

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