Exploring possibility to improve frequency properties of 1200V and 1700V IGBT and FRD with partially diffused proton beam

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Abstract. Authors research a technology to improve frequency properties of IGBT and FRD using a partially diffused high-energy proton beam, and demonstrate a possibility to use this technology to manufacture fast and ultrafast IGBT and FRD for frequencies within 20-50 kHz.

1. Introduction

Many contemporary power electronic devices such as auxiliary power sources, electric drive controllers for industry and transportation, static compensators and HVDC equipment for power grids are based on frequency converter units. One of the main trends in the evolution of such devices is the growing frequency of the inverter unit providing the reduction in weight, dimensions, and cost of passive elements.

This problem can be fundamentally solved using switches based on wide gap semiconductor materials (SiC or GaN) allowing to operate in the frequency range up to several MHz. However, the cost of wideband gap semiconductor switches is quite high and shows no sign of significant reduction in the nearest future.

The wide-spread low-cost silicon IGBT switches are typically suitable for operation in the frequency range of 1-10 kHz. Nonetheless, the threshold frequency of silicon IGBTs can be significantly improved after certain modifications in their design and production process.

As a result, it is possible to develop technologies allowing to increase permissible switching frequency of a silicon IGBT without significant changes in its cost. This paper describes ways to improve frequency properties of IGBT and prepacked fast recovery diodes (FRD) with a partially diffused proton beam technology.

2. Features of power semiconductors irradiation with partially diffused protons

One of the efficient methods to improve frequency values of bipolar conductivity semiconductors (like IGBT and FRD) is controlling properties of electron-hole couple recombination in their structure layers [1, 2]. Irradiation with light ions and protons, in particular, is one of the most flexible and functional methods to control recombination properties since it allows to modify them locally on the needed depth of the semiconductor structure.

Traditionally, frequency values were optimized with monoenergetic beam irradiation to a depth close to the depth of p-n junction (or “anode” p-n junction in IGBT structure), Figure 1, to create a local layer of increased recombination with the high concentration of recombination centers [3–7].
This concentration of recombination centers defines the “proportion of recombination introduced by the irradiation”, described by value $F_t$:

$$F_t = \frac{1}{\tau_1} - \frac{1}{\tau_0}$$  \hspace{1cm} (1)

where $\tau_0$ and $\tau_1$ are values of charge carriers’ lifetime before and after the irradiation treatment.

In this case, deeper layers of semiconductor structure keep almost intact recombination properties, these are usually changed with additional irradiation treatment (normally with accelerated electrons or gamma-particles).

Irradiation with a partially diffused proton beam [8, 9] makes it possible to achieve a “smooth” distribution of recombination centers (Figure 1). Initial proton energy, in this case, is set to a quite high value. To achieve required residual path of protons in a semiconductor sample, a proton beam with high initial energy is released into atmosphere and directed through a system of energy reducing aluminum screens. The total thickness of such screens is selected to obtain the required residual path of protons in the semiconductor sample, Figure 2.

![Figure 1. Methods of radiation treatment to improve turn-off time of IGBT and FWD. Traditional method: a. $-\frac{1}{\tau_1} \cdot \frac{1}{\tau_0}$ profile after irradiation with monoenergetic light ions (protons, helium), b. – Additional “smoothing” irradiation (electrons, gamma). Alternatively: c - $\frac{1}{\tau_1} - \frac{1}{\tau_0}$ profile after irradiation with partially diffused proton beam.](image)

When the initially monoenergetic protons pass through the “path adjusting” screens, they partially diffuse, causing an “adjustment” of the proton path. It results in a rather diffused the distribution of proton path depths, similar in form to the Gaussian function. It strongly affects the distribution of axial life span: it becomes less “sharp” too. An example of typical profiles obtained after irradiation with a proton beam with initial energy of 24 MeV is shown on Figure 3 [8].

The figure shows the distribution of proton path depth (concentration of implanted hydrogen) and $1/\tau_1 - 1/\tau_0$ value. This graph shows that typical length where the value $1/\tau_1 - 1/\tau_0$ is significantly changed is somewhere around 80-100µm, i.e. in the same magnitude order as the thickness of high-Ohm layer in IGBT and FRD.
Another advantage of the partially diffused beam irradiation technology is possibility to emit the initial beam into the atmosphere, greatly simplifying the irradiation procedure during mass production. In addition, protons in such a beam are also somewhat “diffused” in their angle relative to the axial line of the beam. This, combined with the varying path distance, can significantly reduce the undesirable effect of "shading" when dust particles hit the surface of the irradiated samples. Thus, equipment used for irradiation of semiconductor elements can be much simpler and cheaper in comparison to the traditional technology of irradiation with light ions. This compensates for the increased cost of the proton “gun” itself needed to increase the initial energy of the beam.

Figure 2. Irradiation with protons through a set of aluminum screens for partially diffused beam forming.

Figure 3. Profiles of $1/\tau_1 - 1/\tau_0$ (1) and proton paths (2) distribution after irradiation with a partially diffused beam of protons.

3. Experimental samples and measurement conditions

3.1. Experimental samples
The experiment was based on trench field stop IGBT and soft recovery FRD chips for blocking voltages of 1200 and 1700V.

1700V IGBT and FRD chips are designed for nominal collector (anode) direct current ($I_{\text{nom}}$) 150A. The chips are produced on single-crystal “power” silicon, the thickness of silicone structure is 195µm for IGBT, 250µm for FRD. Chip size: 12.7x12.7 mm for IGBT and 10x10 mm for FRD.

1200V IGBT and FRD chips are designed for nominal collector (anode) direct current ($I_{\text{nom}}$) 200A. The chips are produced on single-crystal “power” silicon, the thickness of silicone structure is 125µm for IGBT, 135µm for FRD. Chip size: 12.6x12.6 mm for IGBT and 9.1x9.1 mm for FRD.

5µm aluminum metallization was formed on emitter contact area of IGBT (anode for FRD), and Ni/Au metallization on collector contact area of IGBT (cathode for FRD) for soldering.

The irradiation was made with a partially diffused beam of protons with initial energy 24 MeV. Screen thickness for proton irradiation was selected to achieve maximal difference of $1/\tau_1 - 1/\tau_0$ value on the borders of high-Ohm semiconductor layers of IGBT and FRD layers, as shown on Figure 1. Irradiation doses varied for different groups of crystals.

3.2. Measurement conditions
Irradiated experimental chips were assembled in MIFA-type power modules [10] following standard manufacturing process of the Proton-Electrotex company. Experimental modules were then tested for their key properties:
- saturation voltage of IGBT collector-emitter ($V_{ce\,sat}$) at a temperature of 25 and 130°C, collector current $I_c = 0.25I_{nom}$ and $I_c = I_{nom}$, gate voltage 15V;
- forward voltage of FWD ($V_F$) at a temperature of 25 and 130°C, anode current $I_F = 0.25I_{nom}$ and $I_F = I_{nom}$;
- IGBT turn-on energy loss – $E_{on}$;
- IGBT turn-off energy loss – $E_{off}$;
- FWD reverse recovery energy loss – $E_{rec}$.

Measurement conditions: bridge connection, temperature 25 and 130°C, collector-emitter voltage 600V (for 1200V IGBT) and 850V (for 1700V IGBT), gate-emitter voltage range ±15V, active resistance in the gate circuit 2.2 Ohm, load inductance 300µH; collector current (diode direct current) varying from 0.4$I_{nom}$ up to 1.5$I_{nom}$.

4. Results

4.1. Results of testing

The main characteristics of IGBT and FRD after the irradiation with various doses are shown in Tables 1 and 2. The irradiation doses are numbered in ascending order. The results of measurements are given for the current equal to $I_{nom}$ and the temperature of 130°C.

### Table 1. Main characteristics of IGBT.

| Irradiation | $V_{c\,nom}$ [V] | $V_{ce\,sat}$ [V] | $E_{on}$ [mJ] | $E_{off}$ [mJ] |
|-------------|------------------|------------------|--------------|--------------|
| No irradiated | 1200 | 2.12…2.15 | 12.5…12.8 | 24.5…24.8 |
| Dose1a | 1200 | 2.61…2.68 | 9.7…9.9 | 16.8…17.2 |
| Dose2a | 1200 | 3.30…3.36 | 7.2…7.3 | 14.1…14.4 |
| Dose3a | 1200 | 4.28…4.35 | 6.1…6.2 | 10.1…10.2 |
| No irradiated | 1700 | 2.78…2.83 | 31.6…31.8 | 45.8…46.4 |
| Dose1b | 1700 | 3.42…3.46 | 26.0…26.4 | 33.6…33.9 |
| Dose2b | 1700 | 4.48…4.57 | 23.5…23.8 | 21.8…22.1 |
| Dose3b | 1700 | 7.39…7.51 | 21.8…22.4 | 17.5…17.8 |

### Table 2. Main characteristics of FRD.

| Irradiation | $V_{R\,nom}$ [V] | $V_{F}$ [V] | $E_{rec}$ [mJ] |
|-------------|------------------|-------------|--------------|
| No irradiated | 1200 | 2.04…2.08 | 17.1…17.3 |
| Dose1c | 1200 | 2.37…2.41 | 9.1…9.3 |
| Dose2c | 1200 | 2.68…2.74 | 6.5…6.6 |
| Dose3c | 1200 | 3.49…3.54 | 4.4…4.6 |
| Dose4c | 1200 | 4.80…4.87 | 3.2…3.4 |
| No irradiated | 1700 | 2.14…2.17 | 41.0…43.2 |
| Dose1d | 1700 | 2.37…2.41 | 34.9…36.2 |
| Dose2d | 1700 | 2.77…2.84 | 24.3…25.3 |
| Dose3d | 1700 | 3.32…3.38 | 21.8…22.4 |
| Dose4d | 1700 | 5.45…5.57 | 14.3…14.9 |
Testing results provide ratios between “inconsistently” related pairs of IGBT and FRD properties, such as $E_{\text{on}}$ and $V_{\text{ce sat}}$, $E_{\text{off}}$ and $V_{\text{ce sat}}$, $E_{\text{rec}}$ and $V_F$. These relationships of properties are shown on Figure 4, 5.

Thus, the proposed technology allows to reduce $E_{\text{off}}$ and $E_{\text{rec}}$ by 2.5-3 times, $E_{\text{on}}$– by 1.5–2 times. The physical meaning of reduced energy losses for IGBT turn-off processes and FWD reverse recovery is quite transparent, since a significant part of switching energy losses is related to the charge of accumulated excessive electron-hole pairs in the layers of the semiconductor structure, and its value is “controlled” by recombination centers introduced with irradiation. The experimentally obtained identical relationship for $E_{\text{on}}$ when IGBT is turned on is explained, apparently, not by the reduced amount of excess electron-hole pairs in the layers of the IGBT itself, but rather by a decrease of their amount (after irradiation) in the “opposite” layers in the FWD bridge circuit, where reverse recovery takes place at the same time with turning on the IGBT.

It should also be noted that reduction of $E_{\text{off}}$ and $E_{\text{on}}$ “saturates” with increased irradiation dosage, i.e. $E_{\text{off}}$ and $E_{\text{on}}$ aim for certain minimal values different from zero.
4.2. Possibility of using IGBT and FRD with improved frequency properties in power electronics equipment

Experimental results suggest that the described technology allows to produce ultrafast 1200V IGBT modules with an operating frequency of 60kHz, and 1700V IGBT modules with an operating frequency of 30kHz. To illustrate this statement, consider operation of the ultrafast IGBT modules in two variants of auxiliary power sources.

Auxiliary DC-DC power source is based on a step-down IGBT chopper circuit, Figure 6.

For variant 1, \( V_{\text{in}}=550\) V, \( V_{\text{out}}=300\) V, output current 90A (power 27kW). An Ultrafast 1200V IGBT module is used. Converter frequency is 50kHz.

For variant 2, \( V_{\text{in}}=1000\) V, \( V_{\text{out}}=550\) V, output current 50A (power 27.5kW). An Ultrafast 1700V IGBT module is used. Converter frequency 25KHz.

![Figure 6. Circuit diagram of the auxiliary power source.](image)

Figures 7, 8 show the calculated components of power loss in semiconductor elements of the circuit. Power loss was calculated for the most load-heavy operation mode, the diagram shows components of IGBT and FRD energy loss in the current conducting state (\( P_T(\text{IGBT}) \) and \( P_F(\text{diode}) \) respectively), as well as switching power losses for the IGBT turn on and turn off or for the diode reverse recovery.

![Figure 7. Power losses in semiconductor components of 1200V module at 50 kHz.](image)

![Figure 8. Power losses in semiconductor components of 1700V module at 25 kHz.](image)

5. Conclusions

Using a beam of partially diffused protons makes it possible to develop a low-cost, high-yield technology of manufacturing fast and ultrafast power IGBTs, allowing to use such devices in power electronic converters operating at 20-30kHz.

However, there is still a question - does the proposed technology offer advantages in terms of \( V_{\text{ce sat}} \) and \( E_{\text{on}} \), \( V_{\text{ce sat}} \) and \( E_{\text{off}} \), \( V_F \) and \( E_{\text{rec}} \), compared to the traditional one? The authors plan to study this problem continuing their work.
Proton-Electrotex plan to use this technology to launch a series of fast and ultrafast IGBT modules for 1200 and 1700V at nominal current 100–600A. Commercial samples of the new IGBT modules will become available starting from Q3 2019.

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