Improve power thyristor and diode performance with proton irradiation

Vladimir Gubarev, Alexander Semenov, Alexey Surma, and Valery Stolbunov - February 19, 2019

Control of recombination features in the layers of the semiconductor element is considered to be one of the most effective methods of increasing performance and many other characteristics of power semiconductor devices (PSD). Some aspects of such technologies, based on the accelerated proton irradiation of Silicon elements, are described in this article.

An automatically-controlled operation line for proton irradiation of PSD, helps to selectively introduce the recombination centers and implant hydrogen atoms into the silicon element at a depth of up to 1000 µm.

Some characteristics of fast thyristors, produced with the help of proton irradiation technology, are listed here. The semiconductors have remarkably low turn-off time, small recovered charge, and low peak reverse recovery current.

Implanting hydrogen atoms, during proton irradiation, helps to build local hidden n-layers with low specific resistance inside the n-layer of the semiconductor element. The possibilities of using such hidden layers to produce power diode-thyristors (dynistors) and semiconductor voltage suppressors with increased power capacity are described as well.

Industrial technological complex of proton irradiation

In collaboration with the Institute of Theoretical and Experimental Physics and the All-Russian Electrotechnical Institute, Proton-Electrotex has developed a low-cost industrial technology for proton irradiation of semiconductor devices (Figure 1).

The basis of the technological complex is a 24 MeV linear proton accelerator. The technological complex contains the box for placing cartridges with semiconductor structures before and after irradiation, the mechanical system for moving and positioning the irradiated structures, equipment for the control of irradiation dose and proton beam characteristics, and mobile aluminum screens for control of proton path length in a semiconductor structure. The special screen for the beam dissipation, in aggregate with the mechanical system for moving and positioning the irradiating structures, ensures the irradiation of the wafer with diameters up to 125 mm.

The technological complex gives the following possibilities:

1. Continuous irradiation of large device lots. It is possible to irradiate up to 270 semiconductor elements with diameter of 95-105 mm, up to 360 elements with diameter of 75-80 mm, up to 450 elements with diameter of 40-60 mm, or up to 900 elements with diameter of 24-32 mm in a work
cycle.

2. A short processing time period. The duration of one work cycle is 4-5 hours, including the post-irradiating storage time necessary for reducing the radioactivity of semiconductor elements and technological cartridges up to the safe level.

3. The irradiation occurs in an air environment; a vacuum is not required in the work zone.

4. Control of proton beam characteristics and irradiation dose. It is possible to control the distribution of current density and energy spectrum of protons within the working zone. These measurements are carried out by the mosaic current receiver and system of mobile screens during the testing of the proton beam before a work cycle. During a work cycle, the routine control of the irradiation dose by means of beam current receivers is carried out.

5. Remote control of the system of mobile screens to alter proton path length in semiconductor layers of irradiating elements. The control of proton path length in the semiconductor structure is achieved by changing the summary thickness of screens, through which a proton beam penetrates, before reaching the semiconductor surface. The proton path length in a silicon element can be altered within 0-1000 µm with a step of 20 µm.

6. High level of radiation safety.
Proton irradiation makes it possible to build hidden layers with reduced carrier lifetime inside of the semiconductor element as well as hidden layers with implanted hydrogen atoms. Typical technology distributions over the depth of the silicon element are shown in Figure 2.

These are:
where $t_0$ and $t$ are the carrier lifetime before and after irradiation and implanted hydrogen concentration. Changing proton path length, $R_p$, with the help of aluminum screens, enables the depth of the layers to be adjusted.

The layers with reduced carrier lifetime are successfully used in many types of power semiconductor devices to optimize their dynamic characteristics \cite{1, 2, 3}.

Implanted hydrogen stimulates centers of donor types inside silicon similar to donor dopants, which help to build hidden layers with changed specific resistance \cite{4}. Building such layers allows the improvement of the features for high-voltage suppressors and diode-thyristors, and the integration of these protective elements inside the structure of other semiconductor devices.

\begin{equation}
\frac{1}{\tau} - \frac{1}{\tau_0},
\end{equation}

The application of this technology has allowed for production of a series of fast thyristors with reduced reverse recovery charge.

Such devices have a number key features:

1. Lifetime control by proton irradiation of the cathode side of the thyristor element. The region of the proton path termination in the silicon element is located close to the anode of the p-n junction. Thus the lifetime close to the anode of the p-n junction, $(ta)$, can be $2\times$ to $3\times$ less than the lifetime close to the collector p-n junction $(tc)$. Such an axial lifetime profile allows for the optimization of the relationship between VTM and Qrr: the $1.5\times$ to $2\times$ reduction of the Qrr value at the same VTM value is possible by using this axial profile instead of a traditional uniform profile.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure.png}
\caption{The series of fast thyristors with small reverse recovery charge}
\end{figure}
2. The dense grid of cathode short elements. Cathode shorts are distributed within the emitter area; the next elements are located at the distance about 400 µm. This cathode short grid allows quite a short turn-off time at a rather large lifetime close to the collector p-n junction.

3. Distributed amplifying gate (Figure 3). The distributed gate, together with rather high values of lifetime close to collector p-n junction and in the p base, provide fast turn-on of all the thyristor areas, reduced turn-on loss energy, and increased repetitive di/dt-rate and operating frequency.

Figure 3 The silicon elements of thyristors have diameters of 32, 40, 56, or 80 mm.

Hidden H-Induced layers with reduced resistivity constant
The relationship between allowable ranges of $Q_r$ and $t_q$, blocking voltage ($U_{DRM}$, $U_{RRM}$), average current ($I_{TAV}$), and other parameters and characteristics of new thyristors, are presented in Table 1.

Owing to the reduced $Q_r$ and $t_q$ values, new thyristors can operate in the frequency band up to 30kHz for the 1000-1500V blocking voltage range, up to 10kHz for the 2200V blocking voltage range, and from 2-5 kHz for the 3400V blocking voltage range. The topology of the thyristor element is adapted for high frequencies. New devices can reliably operate at repetitive di/dts of 800-1250 A/µs.

Table 1
Table 92

<table>
<thead>
<tr>
<th>Type</th>
<th>$V_{DRM}$, $V_{RRM}$</th>
<th>$I_{DRM}$, $I_{RRM}$</th>
<th>$I_{TSM}$</th>
<th>$I_{TAV}$ (T.C.)</th>
<th>$U_{TH}$</th>
<th>$U_{TM}$</th>
<th>$Q_{rr}$</th>
<th>$t_{q}$</th>
<th>$R_{m2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>V</td>
<td>mA</td>
<td>kA</td>
<td>A/μs</td>
<td>A/°C</td>
<td>V</td>
<td>V/μs</td>
<td>μs</td>
<td>°C/W</td>
</tr>
<tr>
<td>TFI133-400</td>
<td>300...1000</td>
<td>50</td>
<td>7</td>
<td>1500</td>
<td>400(90)</td>
<td>2,4</td>
<td>1000</td>
<td>100</td>
<td>0,04</td>
</tr>
<tr>
<td>TFI143-400</td>
<td>800...1500</td>
<td>70</td>
<td>8</td>
<td>2000</td>
<td>400(90)</td>
<td>2,65</td>
<td>1000</td>
<td>100</td>
<td>0,03 2</td>
</tr>
<tr>
<td>TFI143-500</td>
<td>800...1500</td>
<td>70</td>
<td>9</td>
<td>2000</td>
<td>500(85)</td>
<td>2,4</td>
<td>1000</td>
<td>200</td>
<td>0,03 2</td>
</tr>
<tr>
<td>TFI143-630</td>
<td>800...1500</td>
<td>70</td>
<td>10</td>
<td>2000</td>
<td>630(80)</td>
<td>2,3</td>
<td>1000</td>
<td>250</td>
<td>0,03 2</td>
</tr>
<tr>
<td>TFI243-400</td>
<td>1200...2200</td>
<td>70</td>
<td>8</td>
<td>2000</td>
<td>400(88)</td>
<td>2,65</td>
<td>1000</td>
<td>300</td>
<td>0,03 4</td>
</tr>
<tr>
<td>TFI243-500</td>
<td>1200...2200</td>
<td>70</td>
<td>9</td>
<td>2000</td>
<td>500(85)</td>
<td>2,4</td>
<td>1000</td>
<td>300</td>
<td>0,03 4</td>
</tr>
<tr>
<td>TFI243-630</td>
<td>1200...2200</td>
<td>70</td>
<td>10</td>
<td>2000</td>
<td>630(80)</td>
<td>2,3</td>
<td>1000</td>
<td>350</td>
<td>0,03 4</td>
</tr>
<tr>
<td>TFI143S-500</td>
<td>300...1000</td>
<td>70</td>
<td>9</td>
<td>2000</td>
<td>500(85)</td>
<td>2,4</td>
<td>1000</td>
<td>80</td>
<td>0,03 2</td>
</tr>
<tr>
<td>TFI153-800</td>
<td>500...1200</td>
<td>120</td>
<td>19</td>
<td>2000</td>
<td>800(85)</td>
<td>2,5</td>
<td>1000</td>
<td>290</td>
<td>0,02 1</td>
</tr>
<tr>
<td>TFI153-1000</td>
<td>800...1500</td>
<td>120</td>
<td>20</td>
<td>2000</td>
<td>1600(80)</td>
<td>2,25</td>
<td>1000</td>
<td>300</td>
<td>0,02 1</td>
</tr>
<tr>
<td>TFI153-1250</td>
<td>800...1500</td>
<td>120</td>
<td>21</td>
<td>2000</td>
<td>1250(70)</td>
<td>2,1</td>
<td>1000</td>
<td>350</td>
<td>0,02 1</td>
</tr>
<tr>
<td>TFI253-800</td>
<td>1200...2200</td>
<td>120</td>
<td>17</td>
<td>2000</td>
<td>800(85)</td>
<td>2,5</td>
<td>1000</td>
<td>400</td>
<td>0,02 1</td>
</tr>
<tr>
<td>TFI253-1000</td>
<td>1200...2200</td>
<td>120</td>
<td>18</td>
<td>2000</td>
<td>1600(75)</td>
<td>2,35</td>
<td>1000</td>
<td>450</td>
<td>0,02 1</td>
</tr>
<tr>
<td>TFI253-800</td>
<td>2200...3400</td>
<td>150</td>
<td>16</td>
<td>2000</td>
<td>800(85)</td>
<td>2,6</td>
<td>1000</td>
<td>1000</td>
<td>0,02 1</td>
</tr>
<tr>
<td>TFI153S-800</td>
<td>800...1500</td>
<td>120</td>
<td>18</td>
<td>1600</td>
<td>800(83)</td>
<td>2,6</td>
<td>1000</td>
<td>150</td>
<td>0,02 1</td>
</tr>
<tr>
<td>TFI153S-1000</td>
<td>800...1500</td>
<td>120</td>
<td>19</td>
<td>1600</td>
<td>1600(78)</td>
<td>2,3</td>
<td>1000</td>
<td>250</td>
<td>0,02 1</td>
</tr>
<tr>
<td>TFI173-2000</td>
<td>1000...1200</td>
<td>300</td>
<td>48, 5</td>
<td>2500</td>
<td>2000(89)</td>
<td>2,15</td>
<td>1000</td>
<td>220</td>
<td>0,01 0</td>
</tr>
<tr>
<td>TFI273-2000</td>
<td>2000</td>
<td>300</td>
<td>40</td>
<td>2500</td>
<td>2000(85)</td>
<td>2,2</td>
<td>1000</td>
<td>800</td>
<td>0,01 0</td>
</tr>
<tr>
<td>TFI373-1600</td>
<td>2000...2800</td>
<td>300</td>
<td>34, 5</td>
<td>2500</td>
<td>1600(90)</td>
<td>2,26</td>
<td>1000</td>
<td>1250</td>
<td>0,01 0</td>
</tr>
<tr>
<td>TFI473-1600</td>
<td>3800...4000</td>
<td>300</td>
<td>30</td>
<td>2500</td>
<td>1600(85)</td>
<td>2,4</td>
<td>1000</td>
<td>3000</td>
<td>0,01 0</td>
</tr>
</tbody>
</table>

Relationship between allowable ranges of $Q_{rr}$ and $t_q$, blocking voltage ($U_{DRM}$, $U_{RRM}$), average current ($I_{TAV}$), and other parameters and characteristics of new thyristors.

Power devices with hidden H-Induced layers that have reduced resistivity constant

Symmetric voltage suppressors with improved power capacity

Figure 4 shows a symmetric avalanche voltage suppressor with a “conventional” structure and a new device containing hidden n-layers with reduced specific resistance.
For "conventional" structure devices, the problem area limiting peak values of dissipation power and avalanche current as well as maximum admissible energy loss, is the periphery area adjacent to the bevel. In this area, with any polarity voltage applied—current density is increasing, and heat dissipation is very poor because the upper contact size is smaller than the semiconductor element.

The new structure device doesn’t have that problem: there is no avalanche current in the periphery areas. This helps to increase the peak avalanche current, peak dissipation power, and energy loss.

Characteristic curves of current and voltage of the symmetric avalanche suppressor with the new structure are shown in Figure 5. The diameter of the semiconductor element is 32 mm, and the avalanche breakdown voltage is -1650 V.
High-voltage impulse diode-thyristors

High-voltage impulse diode-thyristors can be produced via 4-layer thyristor elements with an integrated transistor element–voltage suppressor (Figure 6).

The thyristor element is the main component of the device, and in this case it plays the role of a high peak current switch. The avalanche current integrated into the device three-layer suppressor, switches the thyristor element. If the thyristor has multiphase regeneration control, this element may be located within any of the amplifying areas or even within all of them.

This device can be used as a high power, fast protective element or current and voltage impulse switch with high rise time rates. Oscillograph traces of current and voltage at the switching of the experimental diode-thyristor are shown in Figure 7. The semiconductor element of this diode-thyristor is shown in Figure 8.
Figure 6 High-voltage impulse diode-thyristors are produced on the basis of 4-layer thyristor elements with integrated transistor element–voltage suppressor.

Figure 7 Impulse current switching with rise time rate of (a) about 5 kA/μs and (b) about 200 kA/μs.

Figure 8 Semiconductor element of the diode-thyristor.

Vladimir Gubarev, Alexander Semenov, and Alexey Surma are from Proton-Electrotex, and Valery Stolbunov is from the Institute of Theoretical and Experimental Physics.

References

