Applying Proton Irradiation for Performance Improvement of Power Semiconductors

Control of recombination features in the layers of the semiconductor element is considered to be one of the most effective methods to increase performance and many other characteristics of power semiconductor devices. Some aspects of such technologies based on the accelerated proton irradiation of the silicon elements such as automatically controlled operation line for proton irradiation is being described in the article, which helps selectively introduce the recombination centers and implant hydrogen atoms into the Silicon element at a depth of up to 1000μm. **V. N. Gubarev, A. Y. Semenov, A. M. Surma, Proton-Electrotex JSC, Orel; and V. S. Stolbunov, Institute of Theoretical and Experimental Physics, Moscow, Russia**

Fast thyristors produced with help of proton irradiation technology have remarkably small turn-off time, small recovery charge and 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. Using such hidden layers can produce power diode-thyristors (dynistors) and semiconductor voltage suppressors with increased power capacity.

Industrial technological complex of proton irradiation

In collaboration with the Institute of Theoretical and Experimental Physics and All-Russian Electrotechnical Institute, "Proton-Electrotex" has developed a low-cost industrial technology for proton irradiation of semiconductor devices shown in Figure 1. The basis of the technological complex is a 24MeV linear proton accelerator (see Figure 2). The technological complex contains the box for placing cartridges with semiconductor structures before and after irradiation (4), the mechanical system of moving and positioning the irradiating structures (6), equipment for the control of irradiation dose and proton beam characteristics (7, 9) and mobile aluminium screens for control of proton path length in a semiconductor structure (8). The special screen for the beam dissipation (11) in aggregate with the mechanical system of moving and positioning the irradiating structures ensure the irradiation of the wafer with diameter up to 125mm.

The technological complex gives the following possibilities:

- Continuous irradiation of large device lots. It is possible to irradiate correspondingly up to 270 semiconductor elements with diameter of 95-105mm, or up to 360 elements with diameter of 75-80 mm, or up to 450 elements with diameter of 40-60 mm, or up to 900 elements with diameter of 24-32mm in a working cycle.
- A short period of processing time. The duration of one working cycle is 4-5 hours, including the post-irradiating

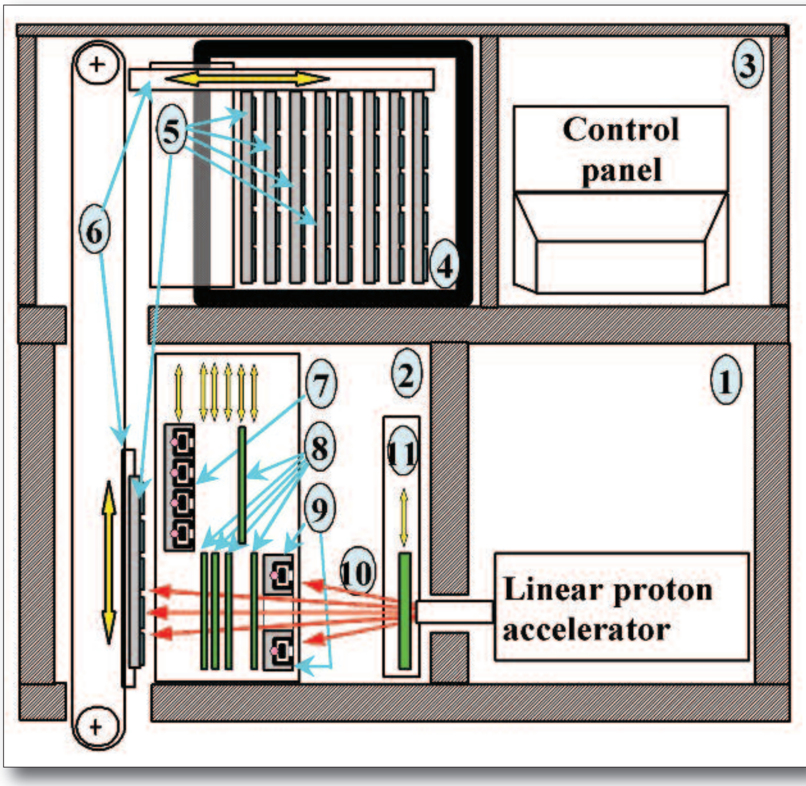


Figure 1: **Industrial technological complex for proton irradiating of semiconductor devices with (1) Proton accelerator room; (2) Irradiation room; (3) Control room; (4) Cartridge box; (5) Cartridges with semiconductor elements; (6) System of moving and positioning cartridges; (7) Matrix of beam current receivers; (8) System of mobile aluminium screens for control of proton path length in semiconductor element; (9) Beam current receivers for the routine control of irradiation dose; (10) Proton beam; (11) Dissipating screen**

LEFT: Figure 2: View of 24MeV linear proton accelerator

storage time necessary for reducing the radioactivity in semiconductor elements and technological cartridges up to the safe level.

- The irradiation occurs in air environment, vacuum is not required in the working zone.
- 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 means of the mosaic current receiver (7) and system of mobile screens (8) at the testing of proton beam before a working cycle. During a cycle the routine control of irradiation dose by means of beam current receivers (9) is carried out.
- Remote control the system of mobile screens (8) to alter proton path length in semiconductor layers of irradiating elements. The control of proton path length in semiconductor structure is achieved by change of the summary thickness of screens, through which proton beam penetrates before reaching the semiconductor surface. The proton path length in a silicon element can be altered within 0-1000µm in steps of 20µm.
- High level of radiation safety.

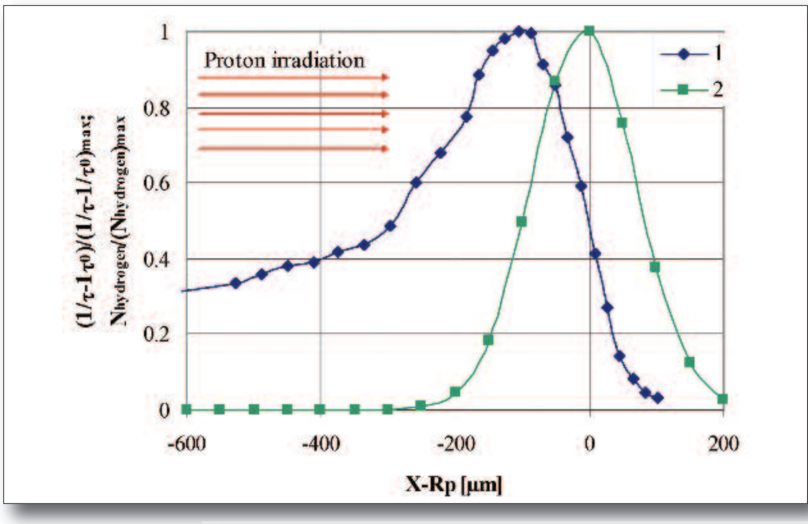
Technology of proton irradiation makes it possible to build hidden layers with reduced carrier lifetime inside the semiconductor element as well as hidden layers with implanted hydrogen atoms. Such technology distributions over the depth of the silicon element are shown in Figure 3. These are according to the following equation

$$1/\tau - 1/\tau_0$$

where τ_0 and τ - carrier lifetime before and after irradiation, and implanted hydrogen concentration as well. Changing proton path length R_p with the help of aluminum screens the needed depth of the layers can be adjusted.

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

Implanted hydrogen stimulates centers of donor type inside Silicon similar to donor dopants, which helps to build hidden layers with changed specific resistance [4]. Building such layers allows improving the features of high-voltage suppressors and diode-thyristors, and integrating these protective elements inside the structure of other semiconductor devices.



ABOVE Figure 3: Proton distribution over the depth of the silicon element

RIGHT Figure 4: Silicon elements of thyristors which can have diameters 32, 40, 56, 80mm

Fast thyristors with small reverse recovery charge

This technology has allowed production of fast thyristors with reduced reverse recovery charge. Such devices hold a number of the following key features:

- Lifetime control by proton irradiation of cathode side of thyristor element. The region of proton path termination in silicon element is located close to anode p-n junction. The lifetime close to anode p-n junction ($^1/_{100}$a) can be in this case 2x to 3x less, than lifetime close to collector p-n junction ((τ/a). Such axial lifetime profile allows optimization of the relationship between V_{TM} and Q_{rr}: the 1.5x to 2x reduction of the Q_{rr} value at the same V_{TM} value is possible by using this axial profile instead of traditional uniform profile.
- The dense grid of cathode short elements. This cathode shorts are distributed within the emitter area, the next elements are located at the distance about 400µm. Such cathode short grid allows obtaining quite short turn-off time at rather large lifetime close to collector p-n junction.
- Distributed amplifying gate (Figure 4). The distributed gate together with rather high values of lifetime close to collector p-n junction and in p base provide fast turn-on of all the thyristor area, reduce turn-on loss energy, increase repetitive

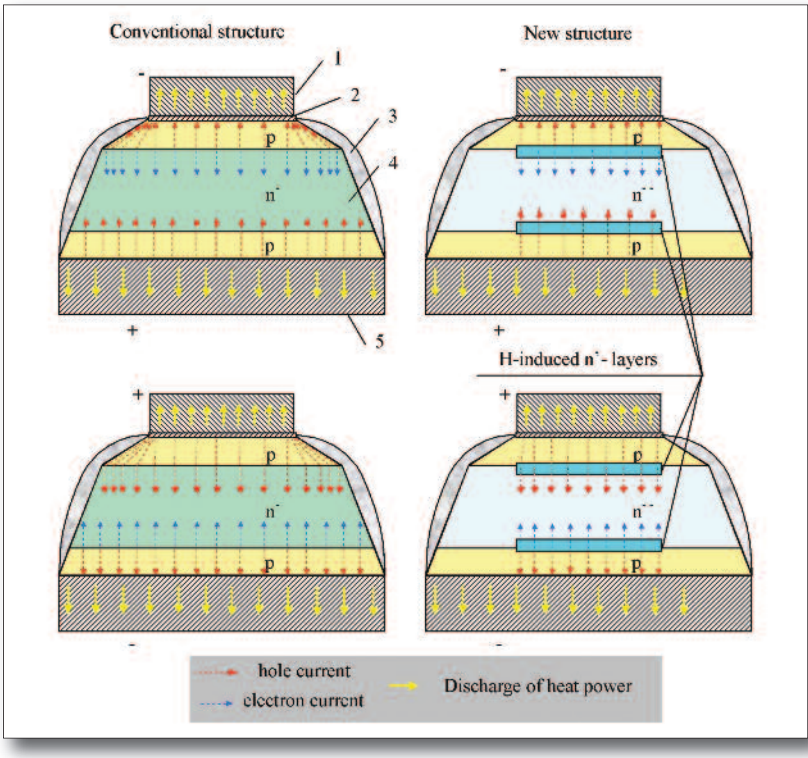


Figure 5: Symmetric avalanche voltage suppressor with "conventional" structure and new device containing hidden n-layers with reduced specific resistance; (1) Copper contact of the package, (2) Contact metallization of semiconductor element, (3) Filler, (4) Semiconductor element, (5) Molybdenum thermal compensator

di/dt-rate and operating frequency.

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

Hidden H-induced layers with reduced resistivity

Symmetric avalanche voltage suppressor with "conventional" structure and new device containing hidden n-layers with reduced specific resistance are shown in Figure 5.

For "conventional" structured 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 bevel. In this area with any polarity voltage applied current density is getting higher, and heat dissipation is very poor because the upper contact size is smaller than thesemiconductor element.

New structured devices doesn't have such problem - there is no avalanche current in the periphery area. This helps to increase peak avalanche current, peak dissipation power and energy loss. Characteristic curves of current and voltage of experiment symmetric avalanche suppressor with the new structure are shown in Figure 6. Diameter of the semiconductor element is 32mm, avalanche breakdown voltage - 1650V.

High-voltage impulse diode-thyristors

Power high-voltage impulse diode-thyristors can be produced on the basis of 4-layer thyristor elements with integrated transistor element - voltage suppressor, shown in Figure 7.

A thyristor element is the main component of the device, the thyristor in this case plays the role of high peak currents switch. Avalanche current of integrated into device three-layer suppressor switches the thyristor element. If the thyristor has multiphase regeneration control, this element may be located within

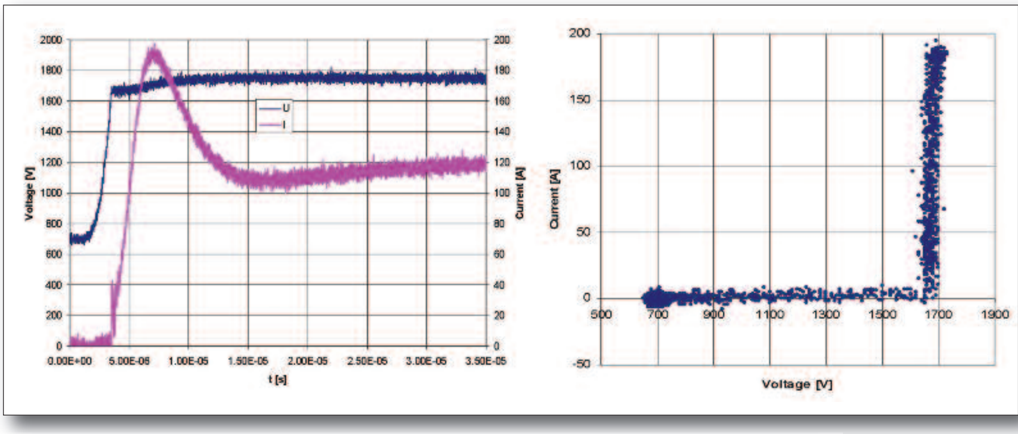


Figure 6: Characteristic curves of current and voltage, temporal variation curves of current and voltage (left) and isothermal dynamic volt-amps diagram (peak impact power 300kW, energy loss up to 150J with single impulses (right)

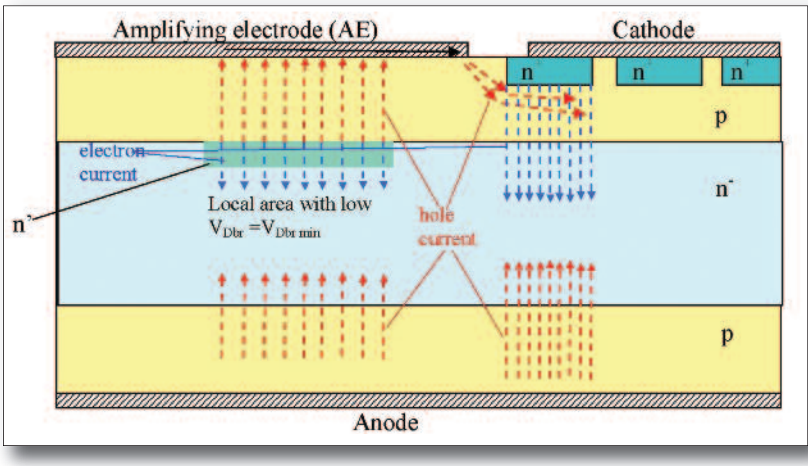


Figure 7: High-voltage impulse diode-thyristors

any of the amplifying areas or within all of them.

Such device can be used as a fast high-power protective element or current and voltage impulse switch with high rates of rise. Oscillograph traces of current and voltage at switching of experiment diode-thyristor are shown in Figure 8. Semiconductor element of this diode-thyristor is shown in Figure 9.

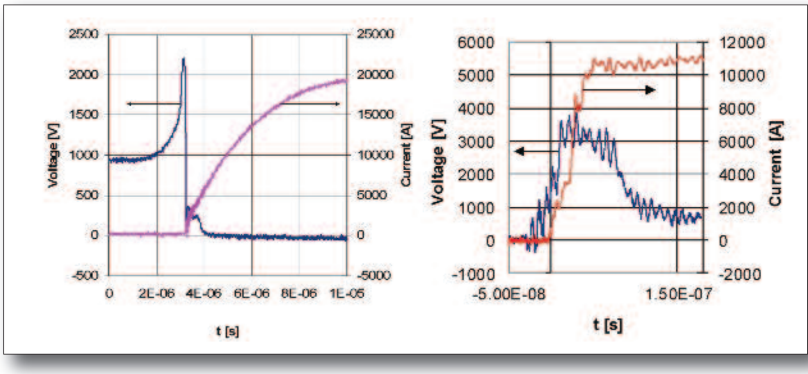


Figure 8: **Impulse current switching with rate of rise about 5 kA/µs (left) and 200kA/µs**

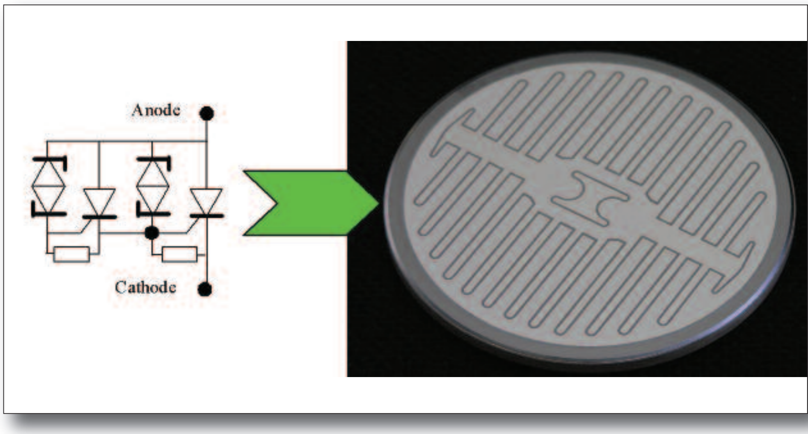


Figure 9: **Diode-thyristor semiconductor element**

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