

Accelerator-based electron beam technologies for modification of bipolar semiconductor devices

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Abstract. Radiation processing technologies for static and dynamic parameters modification of silicon bipolar semiconductor devices implemented. Devices of different classes with wide range of operating currents (from a few mA to tens kA) and voltages (from a few volts to 8 kV) were processed in large scale including power diodes and thyristors, high-frequency bipolar and IGBT transistors, fast recovery diodes, pulsed switching diodes, precise temperature-compensated Zener diodes (in general more than fifty 50 device types), produced by different enterprises. The necessary changes in electrical parameters and characteristics of devices caused by formation in the device structures of electrically active and stable in the operating temperature range sub-nanoscale recombination centres. Technologies implemented in the air with high efficiency and controllability, and are an alternative to diffusion doping of Au or Pt, γ -ray, proton and low-Z ion irradiation.

1. Introduction

The development of physics theory and experimental equipment and methods in radiation material science during the second half of the 20th century, as well as actively seeking of new technology tools for solid-state electronics and semiconductor devices have led to the formation and application of radiation technologies in semiconductor manufacturing process due to their high efficiency. Design and creation of high-performance, high-reliable, easy-to-use and maintain electron beam accelerators with energies up to 10 MeV, fundamental improvement of individual functional units [1-6], established leading position of radiation technologies based on electron accelerators in today's semiconductor industry in comparison with other methods of radiation treatment. The effectiveness of accelerated electrons able to replace the atoms from crystal lattice sites was shown by different research teams in relation to devices based on silicon and other materials.

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Recombination statistics based upon a single dominant level have been used to predict the relative characteristics of gold-diffused, platinum-diffused, and electron-irradiated silicon power devices [7]. The measured characteristics of power rectifiers are shown to be in good agreement with these calculations. The results are also shown to be applicable to power thyristors. In [8] the impact of the electron and proton beam density onto bipolar transistors parameters modification rate was revealed. Achievement of fast recovery characteristics for silicon power diodes and optimization of pulse power thyristors on industrial batches level was shown in [9-13]. In [14,15] shown that to fulfil the requirements of dynamic and static characteristics of bipolar static induction transistor, the irradiation/anneal processing is crucial. Defect distributions features and silicon power devices parameters modification under electron beam irradiation in a wide energy range studied in [16-18]. Extended capacitance relaxation research method for radiation defects parameters measurements in semiconductors device structures is given in [19].

2. Main features of electron beam technologies

2.1. Main features and advantages

Main features and advantages of electron beam technology for the modification of semiconductor devices as follows:

- possibility of processing in air,
- electron flux density adjustment by beam current and distance from the output window due to scattering in air;
- providing a large processing area due to operation in the scanning mode;
- very ample opportunities for the design and construction of under-beam equipment, including beam control systems and a variety of holders, automated sample delivery systems, free-standing vacuum/environment chamber with a beam input window for special investigations;
- simultaneous pass-through processing of several semiconductor wafers, arranged one behind the other due to deep penetrating ability of accelerated electrons (range in Si about 1–2 cm);
- samples heating by beam and temperature control if necessary;
- small footprint and favorable cost of equipment, easy to use and maintain.

Mentioned advantages make it possible to do a preliminary experiment quickly and realize large volume technology to provide needed combination of electrical parameters for specific device.

2.2. Brief critical analysis of alternative processes

For comparison, we present the main disadvantages of alternative methods. So gold doping process results in a negative growth of reverse currents via p-n junctions and characterizes by low concentration reproducibility from wafer to wafer and within the same wafer. The platinum doping process allows to minimize leakage currents, but does not achieve the maximum rate of recombination values and also characterizes by low reproducibility.

Sources of α -particles provide defects formation at shallow depths (no more than 30 microns), have a small processing area and intensity that limits the range of technological tasks solved and is suitable for low volume processing of small-area wafers or some laboratory experiments.

Widely used for different tasks gamma-ray Co^{60} source creates displacements in semiconductors transferring small amounts of energy; needs a long time and associates with some organizational difficulties. Most sub-nanoscale recombination centers formed have relatively low annealing temperatures and not optimum electrophysical properties.

Proton-based (several MeV-level) technology requires very complex, expensive and energy consuming equipment, which casts doubt on the cost-effectiveness of this tool today yet, due to the difficulty of high volume wafer processing as well. In addition, hydrogen doping can cause different time and current instabilities in some devices. Nowadays real application in device technology is in-air proton irradiation with an initial (in vacuum) energy of 25 MeV [20, 21] equipped with semi-

automatic feeding system, which allows to process with wide (about 60 microns) struggle mechanically strong extended silicon-on-molybdenum power device structures.

3. Experimental results

This section contains recent results obtained by the authors for the devices of different classes that demonstrate possibilities of accelerator-based electron beam technologies. Fig. 1 shows experimental dependence of forward voltage drop U_F as a function of electron fluence Φ_e (after stabilizing annealing) for silicon low voltage (6,4 V) diode structure. Volt-ampere characteristics evolution after electron irradiation is shown in Fig. 2. This structure uses as a compensated one for precise thermally compensated Zener diode. Needed value of $U_F = 0,54$ V could be provided in preliminary Au-doped structures at fluences about $3 \cdot 10^{17} \text{ cm}^{-2}$.

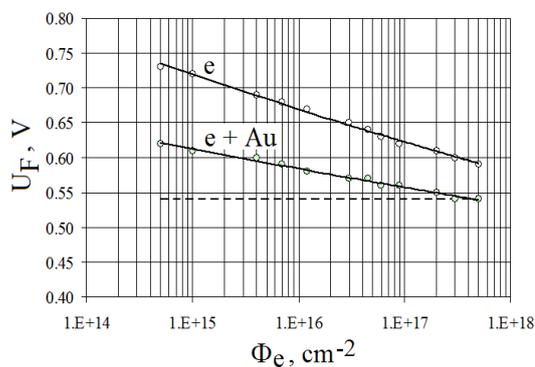


Figure 1. Forward voltage drop in compensated structure of precise Zener diode as function of electron fluence

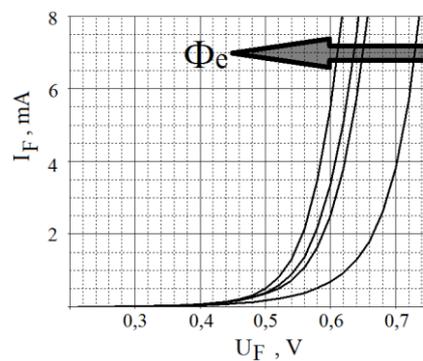


Figure 2. Volt-ampere characteristic evolution after electron irradiation

Regimes of electron treatment and annealing (250 kGy, 380° C) for power high frequency silicon bipolar npn- transistor (5A, 200V) with comb-like structure (Fig. 3) was developed to provide low switching time t_s of 200 ns at needed gain values about 50.

Regimes of electron treatment and annealing (2000 kGy, 350° C) for pulse diode (3A, 200V) with 20 μm epitaxial p+-nn+ structure (Fig. 4) was developed to provide low reverse recovery time t_{rr} of 5 ns at needed forward drop values about 1,2 V.

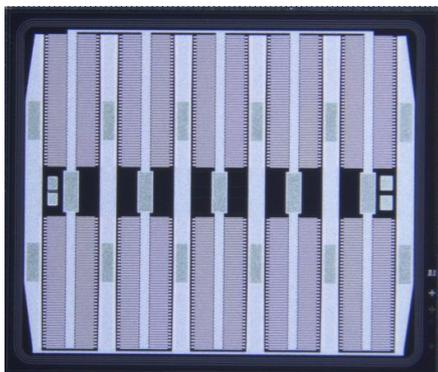


Figure 3. Comb-like structure of power high frequency silicon bipolar npn- transistor (5A, 200V)



Figure 4. Appearance of pulse diode structure (3A, 200V) with guard rings

High power electrical energy converting systems require the use of high-voltage and high-current thyristors, adapted for reliable operation in series and/or parallel connection. Thyristors for parallel and serial connection need the highest identity on-state current-voltage and reverse recovery characteristics respectively. For this purpose technology of precise parameters control of HV HC silicon thyristors by splitting semiconductor elements into specific groups with different initial parameters and control the reverse recovery time of diode-satellites during irradiation. Test diode chips and thyristor elements were made from high resistance NTD silicon with close characteristics to provide high stability of lifetime reduction coefficient values. Test diode structures were $4 \times 4 \text{ mm}^2$ in size and were cut from Al-metallized wafer after anode/cathode diffusion that used for power diode manufacturing. During irradiation test diode structure fixed at the center of the target using contact mandrel that connected with accelerator control unit via a coaxial cable. Lifetime control scheme and control equipment for precise modification of thyristors are shown in Fig. 5 and 6. Typical results of precise modification of thyristor parameters by 8 MeV electron irradiation using the considered above lifetime control hardware are presented. Fig. 7 shows the modification of reverse recovery charge spread for silicon high-voltage thyristors (type T273-1250-44, 1250A, 4400V) after electron-beam treatment. Fig. 8 shows the statistical distribution of on-state voltage drop for the same thyristors.

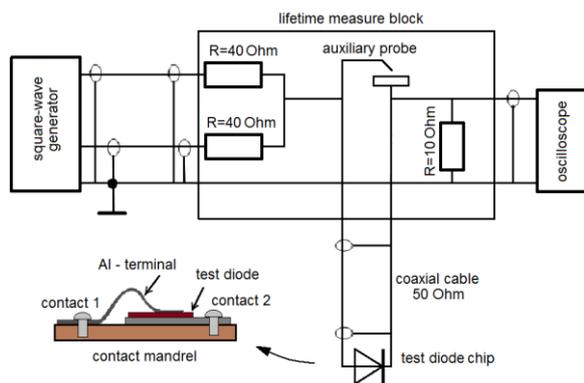


Figure 5. Minor charge carrier lifetime control scheme in test diode structure.



Figure 6. Control equipment for precise modification of high voltage thyristors.

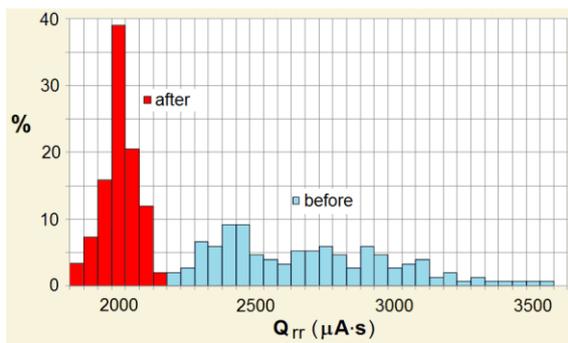


Figure 7. Typical distribution of reverse recovery charge for silicon HVT before and after precise modification by electron beam process

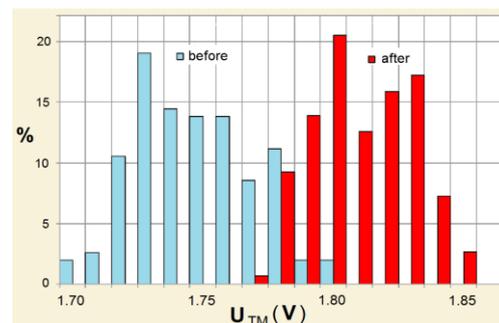


Figure 8. Typical distribution of on-state voltage drop for silicon HVT before and after precise modification

Represented above and some other obtained experimental results useful for real industrial applications summarized in the Table 1.

Table 1. Accelerator-based electron beam technologies realized recently for different bipolar devices

Device type	Task realized	Irradiation fluence (cm ⁻²) or dose (kGy)	Limiting parameter
Compensated p ⁺ /n ⁺ - structure of presice Zener diode (6.5V@7,5 mA)	U _F reduction from 0.64 to 0.54 V for Au-doped structures	3·10 ¹⁷ cm ⁻² . (320°C, 2h anneal)	Irradiation time
Pulsed p ⁺ nn ⁺ -diode (20 μm n-epi base) (1A@200V)	t _{rr} reduction to 5 ns	2000 kGy (350°C, 1h anneal)	U _F increasing
High frequency bipolar transistor with comb-like 'npn' structure (5A@200V)	t _s reduction from 700 to 200 ns	200–300 kGy (390°C, 1h anneal)	Gain reduction to from 60 to 50
Darlington bipolar transistor	Gain, its spread and t _s reduction to optimum values	100–200 kGy (300–390°C, 1–2h anneal)	Gain reduction
Insulated gate transistor IGBT	Switching time reduction	150–250 kGy (330°C, 1 h anneal)	Gain reduction
Fast recovery diode 50A@1700V	Reverse recovery time reduction up to 200 ns	200 kGy (330°C, 1 h anneal)	Reverse current, softness
Fast recovery diode 1, 5, 15A@400, 600V	t _{rr} reduction to 30–120 ns (for different types)	400 kGy (330°C, 1 h anneal)	U _F and reverse current increasing
Welding diode 7.1kA@400V, 600 V	t _{rr} reduction to 3 us, frequency increasing up to 12 kHz	250 kGy (250°C, 4 h anneal)	Middle softness; U _F and reverse current increasing
HC HV Thyristor (different types)	Precise regulation parameters (spread less than 5%)	In situ lifetime control on test structures (<10 kGy)	on-state voltage drop increasing
mc-Silicon solar cell 15% efficiency	Radiation degradation investigation efficiency decreasing to 1 %	1·10 ¹² –5·10 ¹⁶ cm ⁻² .	–
Superluminescent heterostructure diode	Culling structures with hidden defects detection	<40 (+ time to failure)	–

Thus, the accelerator-based electron beam technologies could be effectively applied for manufacturing of competitive traditional and innovative solid state devices, elaboration new approaches in culling methods and radiation hardness investigation.

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References

- [1] Pavlov Yu S and Sharamentov S I 1977 Transistorized Frequency Divider of Microwave Pulses. *Instrum. Exp. Tech.* **20** 149-152

- [2] Pavlov Yu S, Solovev N G and Tomnikov A P 1985 Synchronization Circuit for Shaping Picosecond Accelerated-Electron Pulses *Instrum. Exp. Tech.* **28** 1335-39
- [3] Menshov A N, Pavlov Yu S, Shishko V I, Skvortsov A F, Lukyanov V N and DobrokhotoV V V 1989 Nanosecond Pulse Modulator with Frequency to 250 kHz in Packet Mode *Instrum. Exp. Tech.* **32** 1150-52
- [4] Pikaev A K, Glazunov P Y and Pavlov Yu S 1993 Radiation Center of Institute-of-Physical Chemistry in Moscow *Radiat. Phys. Chem.* **42** 887-890
- [5] Pavlov Yu S, Lagov P B 2015 Magnetic Buncher Accelerator for Radiation Hardness Research and Pulse Detector Characterization. *2015 15th European Conference on Radiation and Its Effects on Components and Systems (RADECS)* 336-338
- [6] Pavlov Yu S, Dobrohotov B B, Pavlov B A, Nepomnyaschy O N and Danilichev V A 2014 Magnetic buncher accelerator UELV-10-10-T-1 for studing fluorescence and radiation physical researches *Proceedings of XXIV Russian Particle Accelerators Conference (RuPAC'2014)* Obninsk, Russia, 259-261
- [7] Baliga J B and Sun E 1977 Comparison of Gold, Platinum, and Electron Irradiation for Controlling Lifetime in Power Rectifiers *IEEE Trans. Electron Devices* **24**(6) 685-688
- [8] Bannikov Yu A, Gorin B M, Kozhevnikov V P, Mikhnovich V V and Gusev L I 1981 Influence of the Flux-Density on the Radiation-Damage of Bipolar Silicon Transistors by Protons and Electrons. *Soviet physics. Semiconductors* **15**(11) 1289-92
- [9] Asina S S, Kuznetsov V M and Surma A M 1986 Using Radiation Technology to Produce Fast-Recovery Power Diodes. *Soviet Electrical Engineering* **57**(5) 74-78
- [10] Asina S S, Surma A M, Goncharenko V P and Ivanov A A 1993 Local Electron Irradiation as a Method of Optimization of the Power Thyristor Pulse Characteristics. *Elektrotehnika* **2** 51
- [11] Ladygin E A, Lagov P B, Musalitin A M, Surma A M, Kokin S A and Uchuvatkin V V 2001 Application of fast electrons for pulse-frequency parameters improving of silicon power diodes and thyristors *Proc. APAM Fifth Topical Seminar, Materials and Processes for Power Electronics Devices* (Moscow) 44-45
- [12] Pisarev A, Surma A and Chernikov A 2013 High voltage thyristor with reduced temperature dependence of reverse recovery characteristics adapted for usage in series assembly *PCIM Europe Conference Proceedings* 953-960
- [13] Surma A and Kislyakov V 2013 Technology of precise adjusting of static and dynamic characteristics of high voltage thyristors *Bodo's Power Systems* **2** 18-21
- [14] Usenko A Y 1993 Using Electron-Irradiation to Control the Turn-Off Time of Static Induction Transistors *Semiconductor Science and Technology* **8**(9) 1715-18
- [15] Usenko A Y 1994 Irradiation-Then-Anneal Processing to Improve BSIT Performance. *IEEE Trans. Electron Devices* **41**(6) 1055-61
- [16] Arinushkin V N, Berman L S, Geifman E M, Konyukhov A V, Lomasov V N, Mnatsakanov T T and Remenyuk A D 1993 Parameters of Force Silicon Diodes Irradiated with Low-Energy Electrons *Zhurnal Tekhnicheskoi Fiziki* **63**(8) 41-45
- [17] Geifman E M, Serezhkin Yu N and Chibirkin V V 1997 Distribution of A centers in basic regions of semiconductor power equipment under electron irradiation *Elektrotehnika* **11** 21-23
- [18] Chibirkin V V and Geifman E M 2002 Radiative Regulation of the Lifetime of Nonequilibrium Charge Carriers in Semiconductor Power Equipment *Russian Electrical Engineering* **73**(5) 76-80
- [19] Goryunov N N, Klebanov M P and Osipov R Yu 1997 Measurer of capacitance relaxation for investigating defects in semiconductors. *Pribory i Tekhnika Eksperimenta* **2** 163-164
- [20] Chernikov A A, Gubarev V N, Stavtsev A V, Surma A M and Vetrov I Y 2011 One more way to increase the recovery softness of fast highvoltage diodes *Proc. of the 2011-14th European Conf. on Power Electronics and Application (EPE 2011), Birmingham, ENGLAND*
- [21] Lazarev N V *et al.* 1996 30 years operation of 25 MeV proton linac I-2 in ITEP at beam current

of 200-230 mA *Proceedings of the XVIII International Linear Accelerator Conference* Ed.
by Hill C, Vretenar M CERN Reports **96**(7) 542-544