Technology of Precise Adjusting of Static and Dynamic Characteristics of High Voltage Thyristors

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Due to capacity growth of inverter units in power semiconductor electronics high voltage and high current thyristors adapted for usage in series and parallel connection are in great demand nowadays.

Thyristors designed for parallel assemblies must have high adequacy of volt-amps diagramm in on-state, thyristor designed for usage in series connection assemblies must have high adequacy of reverse recovery characteristics. General requirement for all applications is presence of identical and preferably minimized temperature dependencies of the above mentioned characteristics.

To achieve identity of the above mentioned thyristor characteristics it is necessary, at first, to provide high precision of donor and acceptant dopants distribution in the layers of semiconductor element of thyristor. Modern technologies and equipment for implantation and diffusion process and usage as blank substrate of high quality “power” neutron-transmutation-doped silicon as a rule allow to solve this issue.

Secondly, it is necessary to ensure identity of carrier lifetime in the layers of thyristor. Solution for this issue for modern high voltage thyristors with voltage over 4000 V has the following difficulties: required for achieving satisfactory low voltage drop in on-state values of carriers lifetime ($\tau$) in n-base of such thyristor equal 100–300 µs, at values and typical distribution of $\tau$ in dispatched groups of initial single-crystalline silicon – 500–1000 µs.

In such a way to achieve drop of $\tau$ in n-base of complete element with required precision (distribution lower than few percent, and sometimes lower than percent portions) will not be possible without initial value of this electrophysical characteristic for this certain semiconductor element.

One of effective technologies of precise regulation of $\tau$ and as a result precise adjustment of thyristor characteristics depending on it is irradiation with accelerated electrons. Decrease of minority-carrier lifetime in device base is in progress due to implantation of radiation-induced defects [1]. Typical dependencies of $1/\tau - 1/\tau_0$ ($\tau_0$ – value before irradiation) in silicon on integral flow (dose) of irradiation D for different particles are shown in figure 1 [2]. Suchwise in the certain area of irradiation doses the following dependency takes place (1):

$$\Delta\frac{1}{\tau} = \frac{1}{\tau} - \frac{1}{\tau_0} = K_\tau D$$ (1)
Experience has shown that during electron irradiation of high resistance “power” “float zone”-grown and neutron-doped silicon value of index $K$ is quite stable and is almost unchanged in the lots of dispatched material, which ensures possibility of precise adjustment of $\tau$ in n-base of semiconductor element. It is necessary, however, to ensure precision and repeatability of irradiation integral flow density (dose) $D$.

The most prevailing method to control irradiation doses with help of Faraday cylinder has fractional error 15–20% during measuring the required for irradiation of high voltage thyristors doses in range $1E11–1E12$ cm$^{-2}$. This doesn’t fully correspond to precision requirements in production of these semiconductor devices and makes search of alternative methods quite important.

One of the most prospective methods is method of direct measurement of $\tau$ on accompanying irradiated objects silicon crystal-satellites. From dependency (1) it is clear that if precision of carrier lifetime measurement is provided and index of radiation degradation $K\tau$ is known, then using $\Delta\frac{1}{\tau}$ it is possible to receive $D$. $K$, and $\tau_0$ values for irradiated thyristor elements and satellite diodes can be different, however, knowing values of $\tau_0$ in each case, and also on condition of high stability of constants $K\tau$, it is always possible to receive $\tau$ value in satellite diode base when in n-base of thyristor element required value of carrier lifetime is achieved.

*Fig. 1. Typical dependencies of carrier lifetime on irradiation flow: 1 – $\gamma$-rays, 2 – electrons 2.5 MeV, 3 – electrons 30 MeV, 4 – fast neutrons.*
achieved. Thus principle of dose control method lies in measurement of degradation of carrier lifetime in test structure during irradiation process and precision of the method will be defined by:

1. Precision of $\tau$ measurement or connected with it characteristics of thyristor element before irradiation;
2. Precision of $\tau$ measurement or in satellite diode base during irradiation;
3. Constancy of $K_\tau$.

Measurement of $\tau$ in base of diode satellite crystals is realized by Lax method [3]. Despite that in connection with real physical value $\tau$ this method can be inaccurate, it has high precision capability with invariable parameters of semiconductor layers and measurement conditions. In our case according to the physical and topological simulation data [4] with impulse characteristics $I_1 = 200 \text{ mA}$, $I_2 = 100 \text{ mA}$ and $t_{\text{imp}}^+ = t_{\text{imp}}^- = 200 \mu\text{s}$ we have the following:

$$\tau = 2t_s$$

where $t_s$ is delay time of reverse voltage.

Satellite diodes are produced on the basis of high resistance neutron-doped silicon, which is close in its characteristics to silicon on the basis of which thyristor elements are produced that ensure stability of $K_\tau$. Satellite diodes' elements are crystals $4 \times 4$ mm cut from the wafers, which went through diffusion process of the power diode. During irradiation satellite diode is buttoned up in the center of the irradiating target in contact snap, from which a coaxial cable is stretched to the accelerator control panel (figure 2).

Fig. 2. Scheme of measurement of carrier lifetime on crystals of satellite diodes during irradiation process.
Typical results of precise adjustment of thyristor characteristics with irradiation by accelerated electrons with energy 6 MeV using the above described control method is the following:

- For lots of thyristors T353-800-35 with average current 800 A and voltage 3500 V, which are used in series parallel assemblies as part of high voltage pulse converters, customers require assurance of distribution of voltage in on-state $V_{tm}$ not bigger than ±0.1 V for even distribution of load in parallel connection of thyristors, and also simultaneous limitation of reverse recovery surge current $I_{rm}$ down to 130 A must be guaranteed. Thyristors are preliminarily grouped according to initial $V_{tm}$ values with 0.05 V interval between groups, and then are being irradiated according the method described above. At that it is possible to lower technological distribution down to $1.8 \, V \leq V_{tm} \leq 1.9 \, V$, which is twice as big of the required (figure 3), and also corresponds to requirements according to $I_{rm}$ (figure 4), herewith general percentage of produced with such characteristics devices exceeds 95%.

- For thyristors T643-320-65 with average current 320 A and voltage 6500 V adapted for series connection, precise technology of reverse recovery charge adjustment allows lowering $Q_{rr}$ variation in lot down to ±70–80 µC (figure 5). $V_{tm}$ variation is also minimized in this case (figure 6).

In figure 7 change of reverse recovery charge distribution in lots of high voltage thyristors T273-1250-44 with current 1250 A and volatge 44 V after precise irradiation process is shown. In figure 8 corresponding statistical distribution of voltage drop in on-state is shown. It is clear that variation of reverse recovery charge in massive lots of thyristors decreases down to value lower than 5%. Variation of voltage drop values in on-state after precise irradiation process is lower than ±0.05 V, which makes it easier, if necessary, to coordinate thyristors’ operation in parallel connection.

In such a way radiating and technological methods of precise adjustment of high voltage thyristors characteristics adapted for usage in parallel-series connection allow decreasing in massive lots of $V_{tm}$ down to values under ±0.05 V with $Q_{rr}$ variation under 5%.
Figure 3. Typical statistical distribution of $V_{tm}$ ($I_{tm}=2500A$) in lots of thyristor elements T353-800-35 before and after precise irradiation with accelerated electrons.

Figure 4. Typical statistical distribution of surge reverse recovery current $I_{rrM}$ ($T_j=125C$, $I_{tm}=800A$, $di/dt=-5A/\mu s$) in lots of thyristor elements T353-800-35 after precise irradiation with accelerated electrons.
Figure 5. Typical statistical distribution of reverse recovery charge $Q_{rr}$ (Tj=125°C, $I_{TM}=320A$, $di/dt=-5A/\mu s$) in lot of thyristor elements T643-320-65 before and after precise irradiation with accelerated electrons.

Figure 6. Typical statistical distribution of $V_{tm}$ ($I_{tm}=2500$ A) in lot of thyristor elements T643-320-65 before and after precise irradiation with accelerated electrons.
Figure 7. Typical statistical distribution of reverse recovery charge $Q_{rr}$ ($T_j=125^\circ$C, $I_{TM}=1250$A, $di/dt=-5$A/$\mu$s) in lot of thyristor elements T273-1250-44 before and after precise irradiation with accelerated electrons.

Figure 8. Typical statistical distribution of $V_{tm}$ ($I_{tm}=4000$ A) in lot of thyristor elements T273-1250-44 before and after precise irradiation with accelerated electrons.
REFERENCES