High Temperature Ultra-fast Gallium Arsenide Rectifier Devices

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Abstract—**The report is related to the high temperature electronics field. The industrial developed country practice demonstrates that up to 70% of the fabricated electrical energy passes through semiconductor converters. Only in the field of electrical drive, which uses about 50% from the produced electrical energy, passing to the frequency converter of the asynchronous drives speed control, brings an energy economy up to 25%. In the electrical transport with the energy braking recovering the economy is more than 30%.**

The present elaboration is foreseeing the improvement of the technological production route of gallium arsenide (GaAs) power semiconductor devices (PSD), by introducing some innovative technological processes as: (1) GaAs epitaxial technology in the Ga-$AsCl_3$-H_2 system; (2) epitaxial structures divided into crystals by chemical method; (3) GaAs p-n junction passivation by own oxide (Ga_2O_3) precipitate on the divided surface of the crystal.

The goal of the project is increasing manufacturing efficiency (ME) at the GaAs power devices with more than 600 V of voltage fabrication. The proposed improvements are increasing ME with 40% and are expanding the blocking voltage interval up to 1000 V. As a result a new product was elaborated and proposed to the manufacturing– the ultra-fast current converter with 80 ns of recovery time, stable at high temperature (200 ^oC) and 4.5 kV of blocking voltage, that outrun the characteristics of commercial product ESJC30-05 (0.3 μs, 110 ^oC).

Keywords-ultra-fastdevice; p-n junction; gallium arsenide; high voltage; high temperature; manufacturing efficiency.

I. INTRODUCTION

Currently the humanity is confronting a worldwide power crisis, which in reality is a global chronic problem, perceived by scientists much before the appearance of this serious environment and social condition by environment pollution with products from organic fuel combustion as carbon or nitride oxides, toxic lead compounds etc. In the industrial developed countries about 70% of the yielded electrical energy is passing through semiconductor converters (SC). Therefore the technical level of those devices has an essential influence on the whole state of the energetics. For example in Russia only 30% of yielded energy passes through SC. Assessments in the aria demonstrated [1] that the development of this ratio up to the worldwide level can reduced the yield of energy in the country up to 12-15%. More essential economization of energy is observed in the electrical drives field, which uses about 50% of the yielded energy. Passing to the asynchronous action drives with frequency semiconductor converter in the rotation speed control brings 25% of energy economization, but in the electric transport with braking energy recovery the economization outruns 30%

It is necessary to notice that the main elements of the converter are the power semiconductor devices, which have a world-fabricated output of more 20 milliards USD and make up 10% from the semiconductor devices market. This industry in Russia has the best development dynamic (20-25%) and is centered on silicon technology. Using new technology and new materials as gallium arsenide (GaAs) represents a continuation of development expectation of those devices.

Concerning energetic losses the problem consists in the silicon (Si) used as cheap semiconductor material, as it possesses reduced electro-physical characteristics (charge mobility of μ_n=1200 $cm^2/V\ s$) at high currents and working p-n junction temperature of 120 ^oC only. From this reason introducing new materials and technologies (for example GaAs μ_n =4000-6000 $cm^2/V\ s$) represents a development perspective of converters production field in the future.
The gallium arsenide (GaAs) advantage in power semiconductor devices has been demonstrated after many investigations, for example in [2, 3]. These works reflect the technological level in the early 80^s. But only in the last 20 years were performed applicative researches and engineering works in this area, which demonstrated the economic efficiency in scientific researches in the power devices manufacturing.

Scientific and Engineering Center "Informinstrument" of Moldova and Commercial Society "Baneasa" Romania fabricated together the experimental output of AD1060P new devices in TO-220 package, of AD1560M in DO4, of AD3060M in DO5, AD2060P in TO-247 at the forward current from 10 A to 35 A, up to 600 V of voltage and reverse recovery time 35-80 ns [6-8].

This study foresees the production technological route modernization of power semiconductor devices (PSD) from GaAs by some innovation technological processes as:

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1. GaAs epitaxy in Ga-$AsCl_3$–H_2 system for obtaining thick (60-80 μ) homogeneous layers;
2. Cutting up in crystals the epitaxial structures by chemical methods;
3. The p-n junction passivation by own oxide Ga_2O_3 deposition on the cut surface of crystal.

II. MODERNIZATION OF TEHNOLOGY

A. Growth of GaAs rectifier structure with 1000 V of voltage

The purity of semiconductor structure growth method is determined at first from the used materials. Row materials, used in the technological experiences by epitaxial route in system Ga-$AsCl_3$-H_2, are industrial products with high quality guaranty [11, 12]. Metallic gallium has the classification Ga=99.9999 (6N), GaAs of АГЧО-1-35б-2(2-18) plates polished on both surfaces with 1.5 inches of diameter and 0.4-0.45 mm of thickness have $2*10^{18}$ cm^{-3} impurity concentration. The semi-insulated Cr doped АГЧПХ-25а plates were used for samples of verification and control of technological parameters. The GaAs plates and arsenic three-chloride ($AsCl_3$) was imported from Ukraine [13].

The experiments demonstrated that growing speed of epitaxial layers, obtained in technological cycle with control of the purity in reaction chamber, is changing from process to process with about 18%. Dispersion of growth speed during the growth is not instrumentally controlled, but can be slowly generated by the instability of the concentration [Ga]/[As] rate in gaseous phase at the first epitaxial process at once after gallium saturation. That is because the saturation process has an aperiodical character, whose stabilization time is determined by descending error once with the gallium flow stabilization. The error is changing more sensitively at the gallium exhaustion from the source.

The experiments of removing the arsenic three-chloride saturation rate in 0.2-1.8 % interval (Fig. 1) demonstrated that starting with 1.0% saturation a layer of poly-crystal GaAs is deposited on the wall of the reaction chamber, but the epitaxial growth speed on semiconductor substrate is diminishing about 26%. As seen on Fig. 1 the growth speed stabilization of epitaxial layer with 42 μ of

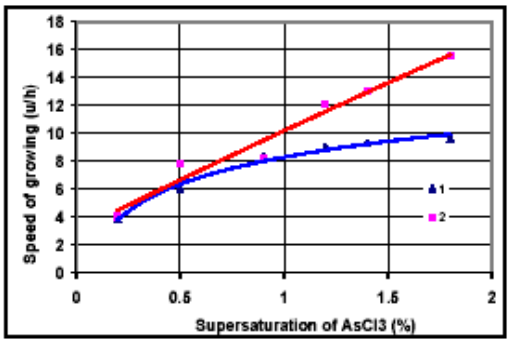


Figure 1. Dependence of the GaAs epitaxial layers growth speed on the function of $AsCl_3$ gaseous flux at the entry of the reactor. 1 - layer 10 μ; 2 – layer 42 μ.

thickness occurs in $AsCl_3$ gaseous flux of 1.0 - 1.8 % supra-saturation rate.

The technological process of epitaxy was investigated on n-GaAs layers during 4 - 6 hours. It was demonstrated, that speed of growing υ = 14 -22 μ/hour is provided by the supra-saturation level control of the gases ($Q = p_{AsCl3}/ p_{H2}$, where p_{AsCl3} and pH2 – partial pressure of $AsCl_3$ and H_2 respectively) at the entrance of reactor, by fixing the temperature interval 80-100 ^oC between gallium source and deposition zone of reactor and by provided high clean level in reaction chamber, it being chemically cleaned before each growing process.

B. The crystal division.

Chemical method of semiconductor structure division becomes efficient for the small dimensions crystal processing and other then right-angled forms.

Elaboration of GaAs crystal division technology was achieved with known outcome utilization [14] and it includes two running process. The first process foresees the covering



Figure 2. The crystals divided by chemical method.

rectifier structure of the metallized GaAs with a sensual varnish layer (AZ4533) with 3 μ of sickness resisting at the oxide solution, the exposition of design from photolithography mask on the light sensual layer, using EM-576 installation and the opening of treated windows by divided developing in solution AZ4562. The second process includes the devising of GaAs structure by etching into HNO_3:HCl solution [14]. The open windows represent the same rings with 2 mm of inside diameter and 0.25 mm of width, through which the semiconductor contacts with the etching solution. Achievement of etching technology is produced by preventive plates washing with opened windows in toluene and their introduction into etching acid solution.

C. Own oxide formation on GaAs surface.

The gallium oxide has more crystallographic modification with respective properties [12]. β-Ga_2O_3 of modification presents an interest for the p-n junction passivation because it has high dielectric properties (9.9-10.2 of static dielectric constant) [15]. This oxide has 1725 ^oC of melting temperature and prepared in special conditions it doesn't dissolve in acids and bases. As own oxide it can be used in GaAs discrete devices fabrication as silicon own oxide is.

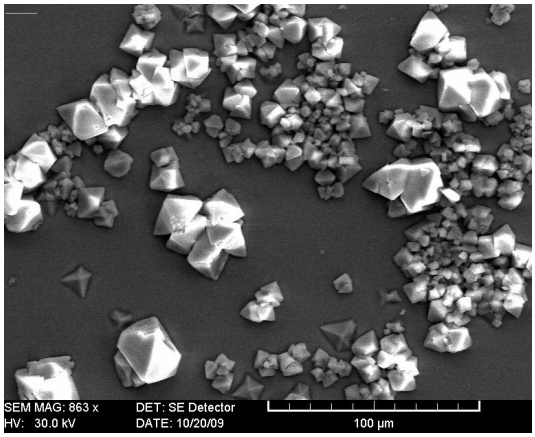


Figure 3. Arsenic oxide crystal selection on GaAs surface in concentrated solution HNO_3: HCl (AFM image).

We established experimentally that processing GaAs plate by concentrated HNO_3:HCl solution the arsenic forms crystalline oxide (III) on the plate surface, as shown in AFM picture Fig. 3. This is a favorable phenomenon for oxide selection process on semiconductor surface with binary composition.

D. Passivation of p-n junction

The investigations result established that the reduction of electric field intensity on p-n junction surface is achieved by covering it with different dielectric layers. In microelectronic industry the silicon dioxide (SiO_2) has a large use, particularly when the device element is built on silicon substrate as being own oxide.

The film of silicon nitride (Si_3N_4) has better adhesive properties on GaAs surface. But its temperature of deposition is outrunning 750 ^oC and can generate the defects in semiconductor structure. Besides, the equipment of Si_3N_4 deposition is more expensive and requires more investments

The chemical method of gallium oxide (Ga_2O_3) deposition on GaAs surface is made up from surface washing in organic dissolvent (toluene) before processing, etching it in the ammonium solution for 3-5 min, abundant washing in deionized water, then introducing the sample in acid solution of 45-70 % concentrated nitric and hydrochloric acids for 0.1-2.0 min. After washing in deionized water and drying the samples are treated at 320-360 ^oC temperature in flux of hydrogen. The time of the thermal processing is selected by the experiment and is established in 12-60 minutes.

As a priority of the technology we notify a simple enough achievement, it does not require big investments. At the room temperature gallium oxide forms with substrate (GaAs) delimitative surface, which has a common element (Ga) with the substrate that improves adhesive properties of the oxide film with substrate. At the oxide deposition by chemical method is not necessary to use electrical current as at electrochemical deposition. The film's oxygen allows surface levels of GaAs, forming depth centers in the energetic band, which stabilizes Fermi level on the surface, thus diminishing the intensity of electric field on the surface of semiconductor.

III. THE CURRENT ELECTRONIC CONVERTER OF HIGH TEMPERATURE

The current converter AD035-45 represents a diodes column which contains high voltage rectifier diodes consecutively connected, assembled and incorporated in plastic with two exit terminal.

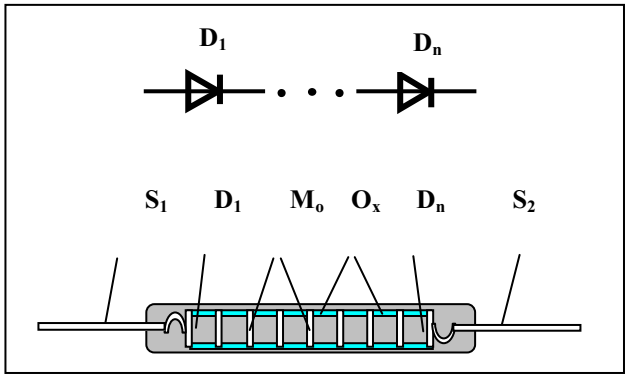


Figure 4. Wiring and rational design (do not a scale) of the electronic converter AD035-45.

The succession of $D_1 \ldots D_n$ elements is shown schematic in Fig. 4 and the construction contains high voltage diodes of the GaAs epitaxial round form structure with the diameter smaller then 5 mm. Passivation layers Q_x were deposited on the exit surface of p-n junction. Metal disks M_o with the value of thermal dilation coefficient (TDC) close to the semiconductor's TDC, as e. g. molybdenum, are assembled between diodes in the axe direction over one or more diodes. The terminals S_1 and S_2 are flexibly jointed with the diodes assembled at the extremes of the column through the metal disk and all these elements were closed in a plastic capsule.

Unlike the prototype, the rectifier diode is fabricated from GaAs by halide vapor phase epitaxy (HVPE), which has a good output in the industrial scale that reduces production costs. This technology permits the efficacious and qualitative fabrication of the rectifier structures with over 1500 V of voltage. Other converter difference refers to the material of he p-n junction passivation layer, which represents the own oxide of the semiconductor – gallium oxide.

A. Technical and consumption advantages of AD035-45 converter

High temperature ultra-fast current converter is shown in Fig. 5.

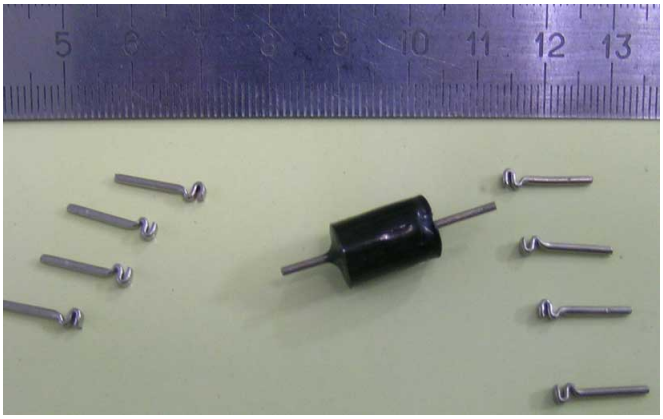


Figure 5. Picture of the GaAs ultra-fast current converter.

TABLE I. **MAXIMUM CHARACTERISTICS**

Parameters	Symbol	ESJC30	AD035-45	Unit	
Repetitive reverse voltage	V_{RRM}	4.5	5.0	kV	
Forward average current	$I_{F(AV)}$	350	350	mA	T_m = 200 °C, Resistive load
Permitted p-n junction temperature.	T_j	120	200	°C	

TABLE II. **ELECTRICAL CHARACTERISTICS**

Parameters	Symbol	ESJC30	AD035-45	Unit	
Forward voltage	V_F	12	8.3 7.6	V	T_j = 25 °C 200 °C
Reverse current	I_r	10	5.8 11.5	μA	T_j = 25 °C, V_R =V_{RRM} 200 C
Recovery time	T_{rr}	300	80	ns	T_j = 25 °C I_F = 100 mA

Current-volt characteristics in direction bias for two operation temperatures (25 °C and 200 °C) is shown in Fig. 6, where we observe a 30 % of energy loss reduction compared to the silicon prototype.

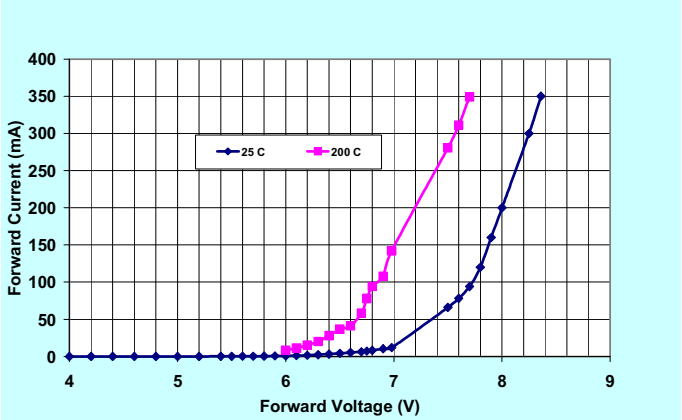


Figure 6. Forward ampere-volt characteristics of AD035-450 current electronic converter.

The proposed modifications of technological route of AD035-450 converter fabrication allow:

- Increasing up to 40% of manufacturing efficiency (ME) of the GaAs rectifier devices with breakdown voltage up to 600 V elaborated in Republic of Moldova.
- Expanding up to 1000 V breakdown voltage of GaAs power devices.
- Diminution of energetic damage with 30%.
- Elaboration and manufacturing of other new performance products as ultra-fast electronic converter with 80 ns of reverse recovery time, 200 °C of operated temperature and 4.5 kV of reverse voltage, which outrun the siliceous ESJC30-05 parameters (0.3μs, 110 °C).

IV. CONCLUSIONS

Advanced technology of GaAs layers growth in Ga-$AsCl_3$-H_2 system demonstrated in scientific and engineering laboratories of Republic of Moldova was put in application for semiconductor power devices manufacturing in high temperature electronics area. Expanding the voltage interval more then 600 V at GaAs ultra-fast power devices is possible by passivating the defected surfaces in crystal division process with own oxide of semiconductor materials.

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