Automation Control System of the Alloying Process of Gallium Arsenide Layers Growth by Epitaxial Technology

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***Abstract*—This paper proposes to control the thermal alloying process of GaAs epilayers growth by transport reaction in Ga-$AsCl_3$-H_2 system. The thermal alloying process is controlled by using the universal two-channel programmable PID-controller TRM151, which permits automatic control of complicated objects with high precision. The thermal process was identified using the parametric model ARX (Auto-Regressive eXogenous) from System Identification Toolbox from MATLAB. The experimental technologist's program contains steps of p^+- p^0 –n^+ photovoltaic structures achievement with damper layer on p-GaAs substrate. There is a possibility to obtain multiple periodical epitaxial layers structures with different dimensions and electro-physical properties, including nano-dimension structures, changing different steps of production. The tuning controller was performed using the maximal stability degree method. This control system minimizes the new technologies elaboration terms, accelerates the implementation of the elaborated technology in industry by reducing production costs, improving the product quality and its market competitiveness.**

Keywords-GaAs epitaxial technology; PID-controller; identification of object; tuning controller; maximal stability degree method

I. INTRODUCTION

The epitaxy technology of semiconductor layers type A^3B^5 by the HVPE chloride method is considered to be one of the purest technologies applied in the microelectronics industry [1]. The research in the domain of gallium arsenide (GaAs) demonstrated that application of this technology in discrete semiconductor elements industry allows to manufacture homogenous semiconductor thick layers (80-100 μ) with surface to 4 inches in the diameter for the competitive devices in the market, such as the ultrafast power rectifier of high temperature [2], converters of high voltage [3], ultra-fast suppressor [4] and optoelectronic devices.

The final purpose of this project is to develop the automatic control system of technological process of growing the semiconductor structures from GaAs through the epitaxy of layers in the gas environment Ga - $AsCl_3$ - H_2. This technology is widespread in industrially developed countries, but the industrial installations with digital control of technological processes is produced in the original country [1] with high price and these installations are not accessible for researchers in developing countries. Research centers from the Republic of Moldova have the type IEC-3/4R laboratory technological installations. They were produced in Moldova and equipped with autonomous control subsystems, controlled by an experienced and qualified operator who needs to have the high qualification and good experience.

The technological laboratory installation is characterized by a relatively extended period of manipulation of technological parameters, which allows the development of new semiconductor devices and new technological processes. The IEC-3/4R installation can not provide competitive economic efficiency.

The elaborated technologies can be applied in the lab conditions, on an industrial scale only by the programming the technologist's knowledge and experience accumulated in the process of designing and transmitting this volume of information to the computer, thus giving the technologist a possibility to elaborate new products.

This paper is aimed at solving a specific technological problem of alloying the GaAs layers in the manufacture of photovoltaic cells (PC) for conversion the concentrated solar energy [5] using the epitaxial method.

Therefore, we have selected the GaAs as one of the most perspective semiconductor materials for manufacture the PC of concentrate energy. The GaAs has the high capacity of solar energy absorption and requires the thickness layer just with a few microns, it has the forbidden energy band practical ideal (1.43 eV) with single-junction PC and the most important is that this semiconductor material is used on a large industrial scale.

One of the prospects of energy conversion efficiency of PC from GaAs is implementation of nano-structured periodical

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layers in the active zone of the device in order to implement quantum effects. This paper presents a technological variant with automatic control of production process with controlled concentration of GaAs by HVPE technology with two alloying elements (Zn, Te) in the $AsCl_3$ - Ga - H_2 system .

II. DESCRIPTION OF THE TECHNOLOGICAL PROBLEM

Technological installation of epitaxy IEC-3/4R is characterized by different technical parameters, whose values can be varied within the limits shown in Table I. The technologist prepares the program of the structure production , for example (p^{++} - p^o - n^o - n^{++}), by setting the value of the parameters at the growing the layer, for example the output time of the system, the quality of control and the stability degree of parameter, duration of action, activation period, etc. Thus being formed, the technological program contains many steps with values of the parameters serving as the database (DB) for the automatic system operation. The computer-adjusted program can be activated several times with a designed precision typical of the technological industrial installation.

The functional scheme of IEC-3/4R installation is presented in Fig. 1. The control thermal system contains six control objects: the chamber of gallium source (Ga), the chamber for the substrates, both installed in the reactor, the chamber for alloying the n-type layer (Te) installed at the reactor entrance, the chamber for alloying the p-type layer (Zn) installed at the reactor entrance, two bubbler B1, B2 with arsenic trichloride ($AsCl_3$). The gas system contains three rotameters R1, R2, and R3 for controlling the flow of the hydrogen (H_2) in the technological process.

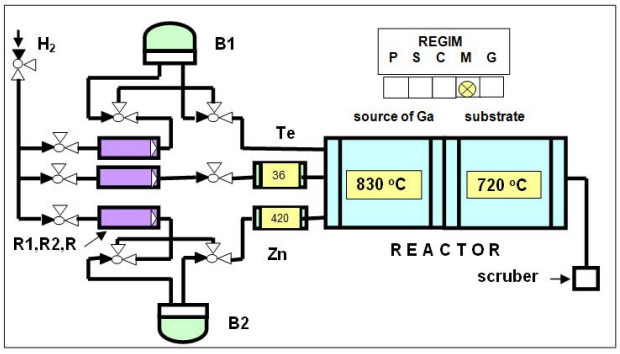


Figure 1. The functional scheme of epitaxy installation of GaAs with transport of reaction.

The technological production cycle includes the technological operation of corrosion the surface substrate purging the reactor with a flow of HCl vapors at the increasing temperature or shifted temperature of 40-50 °C or higher, within the time range of 2-5 min in the reactor growing zone. . After the HCl is injected into the reactor installation, transition to the regime of initiation the growing of the first epitaxial layer (p^{++}) in accordance with photovoltaic structure presented in the Fig. 2.

TABLE I. THE LIST OF CONTROL PARAMETERS OF THE C-3/4R INSTALLATION

Nr.	Name of Parameters	Index	Measure Unit	Value of the Parameters
1	The temperature in the reactor in the zone of increasing	T_S	°C	650-800
2	The temperature in the zone of reactor of the source (Ga)	T_G	°C	760-920
3	The temperature in the zone of reactor of the doping (Te)	T_T	°C	260-360
4	The temperature in the zone of doping source (Zn)	T_Z	°C	320-410
5	Temperature in the room of the gas system	T_K	°C	28-30
6	Temperature in the zone of chloride ($AsCl_3$) source	T_A	°C	19-25
7	Hydrogen consumption through the source channel (Ga)	V_{HG}	cm^3/min	200
8	Hydrogen consumption through the source channel (Te)	V_{HT}	cm^3/min	60
9	Hydrogen consumption through the source channel (Zn)	V_{HZ}	cm^3/min	60
10	Consumption chloride of the ($AsCl_3$), channel (Ga)	V_{AG}	cm^3	
11	Consumption chloride of the ($AsCl_3$), channel (Zn)	V_{AZ}	cm^3	
12	Total consumption of the hydrogen (H_2)	V_H	cm^3	
13	Total consumption of the arsenic chloride ($AsCl_3$)	V_A	cm^3	
14	The integral duration of the technological process	t	min	60-180
15	The duration of state substrate in the stages in process	t_S	min	10-60
16	The integral duration of source state (Ga) in the process.	t_G	min	400-800
17	The integral duration of source state (Te) of doping	t_T	min	200-600
18	The integral duration of source state (Zn) of doping.	t_Z	min	200-600
19	The state of scrubbing		on/off	

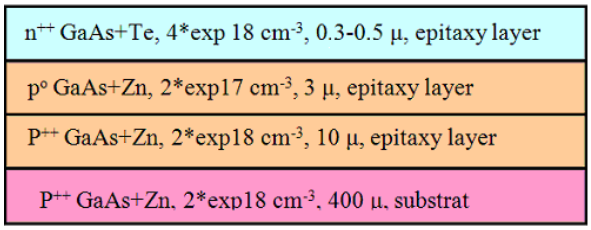


Figure 2. The CFV structure with epitaxial layers of GaAs.

The technologist program for this structure provides alloying damper layer with zinc at the concentration $2x10^{18}$ cm^{-3} by setting the source temperature of Zn equal to 410 °C in proportion with saturated vapors pressure of zinc presented in Fig. 3. The time of alloying process is calculated from the projected thickness data of damper layer and the speed of growing GaAs for this regime. The speed of growing the epitaxial layer is determined experimentally depending on doping degree, which reduces the growth rate from 15-18 μ in the regime without alloying up to 7-8 μ in the regime of alloying with zinc to saturation $2x10^{18}$ cm^{-3} .

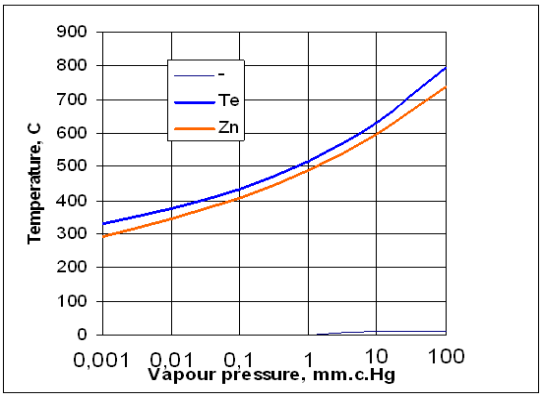


Figure 3. The pressure of saturated vapors of zinc and tellurium at different temperatures.

An important moment regarding the increasing the following damper layer represents minimizing the duration of transition from one type of alloy to another type, and minimization of the duration of transition of growing layers at the different concentrations of impurity (view the time t_7 - t_8) in the technologist program presented in Fig. 4.

The top part in Fig. 4 represents the time temperature distribution two thermal zones of the reactor: the chamber of Ga source and the chamber of growing, which are controlled autonomously by PID controllers and programmed by an operator. The bottom part of the drawing represents the technologist program of alloying of layers in the reactor, which is required to be done and controlled by the computer.

The first layer begins growing at the moment of time t_3 immediately after temperature stabilization in the growth chamber and the stopping of the HCI flow by closing the bubbler B2. When the time constant of Zn heater is known, the moment of time t_2 can be calculated, which represents the time of introducing a current in the circuit, thus the stabilization of regulation the temperature of Zn should coincide with the moment t_3. Thus one can obtain a perfect homogeneity of alliance concentration at the substrate border in the direction of growing the epitaxial layer. It is required to minimize the duration of passing to the smaller concentration of Zn vapor, this time can be minimized, for example, by forcing the cooling of alloying source during the time t_4-t_5 . The same happens at the moment of time t_7, when the circuit of Zn source is disconnected and the amperage current source is introduced in the circuit source of Te (control channel 2).

The end of the process of growing the PC structure occurs at the moment of time t_9, when the circuit source of alloying is disconnected at the time when the thermal circuit of reactor is disconnected.

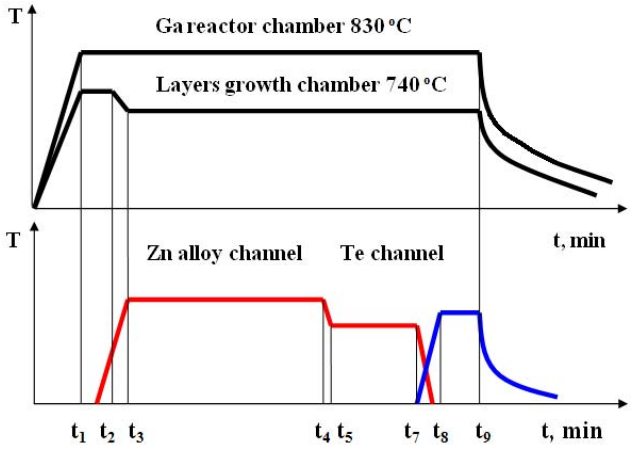


Figure 4. The technologist program of automatic control of GaAs alloying process.

III. Elaboration of Alloying System

Automation of this process has been carried out by applying a universal programmable PID controller with two channels TRM151-0 01 (TU 4211-009-46526536-03), which has extensive possibilities of configuration at the computer [6]. At the entrance of the system two thermocouples TXA have been installed and at the output of the system two converters DA (4-20 mA) have been installed. The auto-tuning function of PID controller is functioning in the TRM151 device thus excluding any manual tuning operation by a user.

The TRM151 controller contains the interface-module RS-485, which allows a computer-based device configuration, and permits the transmission of the current values of measured quantities, through the network permits reception of operative data from network, for generation of the control signals or storage of data in the computer memory.

The basic scheme of automatic command block of thermal regime of alloying is presented in Fig. 5.

Constructive control system is implemented in form of autonomous block which is attached to the epitaxy installation IEC-3/4R in the perspective of full automation of the targeted technology and its implementation in the microelectronics industry.

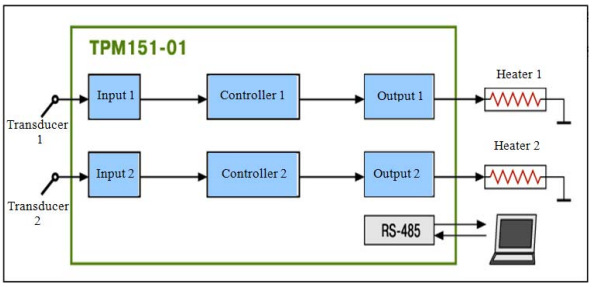


Figure 5. The basic block scheme of automatic control the thermal regime of GaAs alloying process.

Constructive control system is implemented in form of autonomous block which is attached to the epitaxy installation IEC-3/4R in the perspective of full automation of the targeted technology and its implementation in the microelectronics industry.

The general view of automatic command block of thermal regime of alloying GaAs sources in the process of epitaxial growing in the system Ga-AsAl_3-H_2 is presented in Fig. 6.



Figure 6. The general view block of automatic control the alloying sources of epitaxial layers of GaAs.

The TRM151 device performs several basic functions, including the measures of two physical values, controlled by primary converters, controlling physical quantities in accordance with PID law or positional on / off control, changing the setting in concordance with technologist program, transmitting in the network RS-485 the current values of measured quantities and the output signals of the controller and control parameters in the technologist program, stored the parameter values programmed in the memory with autonomous power .

The information network of the system is developed on the basis of AS4 interface converter (TU 4218-003-46526536-2006) in accordance with EIA RS-485 standard. The device is designed for reciprocal conversion of electrical signals of USB and RS-485 interfaces ensure the galvanic isolation of inputs.

The AS4 converter provides the data transmission using the 2-line differential signal and using the additional line for compensation of connection potential with ground. This interface allows to use the communication lines between extreme devices of maximum 1200m in length.

The computer with USB 2.0 interface that is available today, allows data transmission with 480 Mbit / s speed. The USB 2.0 interface and RS-485 are symmetrical and permit data transmission through two lines (D +, D-).

The logical levels are similar to the same levels of RS-485 standard. The interface also contains the alimentation lines Ucc, GND, if the current device does not exceed 500 mA. The novelty of these elaborations consists in transforming the current technological laboratory installation IEC-3/4R in technological installation with industrial capacities and multiplying these installation of production for reviving the electronics industry in the Republic of Moldova.

IV. IDENTIFICATION

The technologist program provides the alloying damper layer with zinc at the concentration $2x10^{18}$ cm^{-3} by setting the source temperature equal with 410 °C in conformity with saturated vapors pressure of zinc. This process of doping with zinc was identified using the parametric model ARX (Auto-Regressive eXogenous) from ARMAX (Auto-Regressive Moving Average with eXogenous inputs) class. The experimental curve of temperature variation in the chamber is presented in Fig. 7, for this curve the identification was made.

$$A(q^{-1})y(t) = B(q^{-1})u(t - nk) + e(t), \quad (1)$$

where $A(q^{-1}) = 1 + a_1 q^{-1} + a_2 q^{-2} + \ldots + a_{na} q^{-na}$;

$B(q^{-1}) = b_0 + b_1 q^{-1} + b_2 q^{-2} + \ldots + b_{nb} q^{-nb}$;

$y(t)$ - output signal;

$u(t - nk)$ - input signal;

nk - number of input samples that occur before the input affects the output, also called the dead time in the system;

$e(t)$ - disturbance signal;

q^{-1} - delay operator.

The estimated vector of parameters are presented as follows:

$$\theta = [a_1\ a_2 \ldots a_{na}\ b_1\ b_2 \ldots b_{nb}].$$

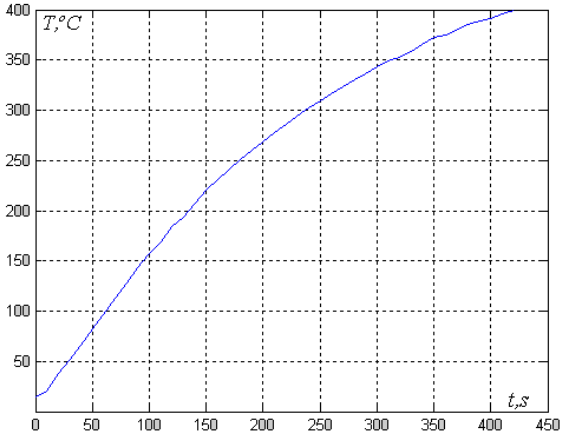


Figure 7. The experimental curve of temperature variation in the chamber.

On the basis of the experimentally obtained data and using the System Identification Toolbox MATLAB, the following

transfer function of the operator q^{-1} of the control object was obtained:

$$H(q^{-1}) = \frac{r_1 q^{-1} + r_2 q^{-2}}{1 - l_1 q^{-1} + l_2 q^{-2}} = \frac{5.284 q^{-1} + 5.284 q^{-2}}{1 - 1.485 q^{-1} + 0.5112 q^{-2}}. \quad (2)$$

The transfer function (2) in the Laplace transform is presented in relation (3).

$$H(s) = \frac{b_0 s + b_1}{a_0 s^2 + a_1 s + a_2} = \frac{-0.08109 s + 0.1455}{s^2 + 0.0671 s + 0.0003607}. \quad (3)$$

The transient process of the identified model process is presented in Fig. 8.

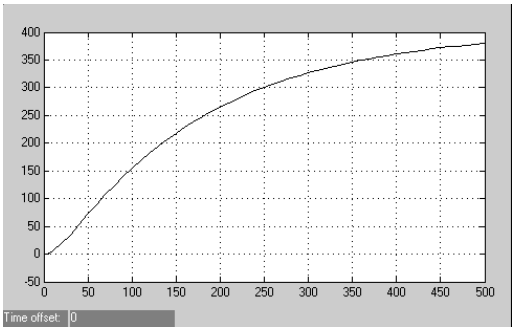


Figure 8. The transient process of the identified model.

V. CONCLUSION

The realization of GaAs epitaxy installation by the transport reactions with automatic control system, opens the researchers of new technologies a range of possibilities for extensive investigation in acceleration, and multiplication of repetitive experimental samples of high quality.

At the present each researcher activating in the domain of elaboration of new technology, feels a need of collaboration with qualified professionals from other fields such as engineering systems and automation of technological processes.

This kind of collaboration minimizes the time of the new technology development and also brings forward the moment of implementing the elaborated technology in the industry by reducing production costs, improving the product quality and its market competitiveness.

The technologist program installed at the automatic control system developed for the alloying GaAs at the epitaxy installation IEC-3/4R may consist of simple steps and the transformation steps , also including operation in the program cycle. Thus, the technologist has a possibility to design and obtain multiple periodical epitaxial structures of different electro-physical dimensions and properties, including nano-dimensional layers.

Nowadays, scientists of the Republic of Moldova should introduce the new technology on an industrial scale, through the automatic control system.

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