Automatic Control Quality of the Alloying Process at the Epitaxial Semiconductor Structure Growth

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Abstract - **The dynamic of automatic system control in conditions of absence of the operate measurement of exit parameter by utilizing a intermediary parameter as may be the control system of gallium arsenide epitaxial layers impurity concentration in alloying process, obtained by transport of reactions in the Ga-AsCl3-H2 gas system, was investigated. Because of purity reasons in the reactor cannot be intro-duced sensors for inside parameter measurement. The au-tomat control system is working by the alloying substance (zinc, tellurium) temperature measuring, which supplies the vapour flow source at the reactor entrance. The vapour flow, generated in the chamber of alloying source and transported it in the reactor by hydrogen flow, is arrived in the growing zone of the reactor with 2-6 min of delay, because the reactor capacity is bigger than alloying chamber capacity. Optimization parameters of the technological process are the time of the reactor filling with vapour and the time of its evacuation after the vapour flow is interrupted. Those parameters are in direct relation with the capacity of the vapour source and they need to be minimized by a forceful overshooting of alloy source temperature.**

Keywords - *gallium arsenide, epitaxial technology, alloying automatic control*

I. INTRODUCTION

The modern industry demonstrates that the technological processes automation becomes decisive in work efficiency increase and output quality improving. The problems of automation are concentrated on designing and adjusting stages of automatic control system (ACS) depending on the technological complexity. Technological process is the adjusting object (AO) or the controlling object and underlies the beginning of an automation project with technical conditions and requirements, which need to be excluded from the abilities of the technologist. When AO equation and the outside acting are known the determinative methods utilization of ACS analysis and synthesis is accepted only for simple system investigations or preventive evaluation of the system behavior for choosing the adjustment parameters [1].

Epitaxial technology of semiconductor layers growing by reaction transport in Ga-$AsCl_3$-H_2 gas system is complex [2] and its utilization on industrial line can be competitive by the automation of the process of adjustment and control. In this process the complications of technology for automation are reduced to the installation impos-sibility of transducers in quarts reactor for measuring the ACS exit parameters. The process takes place in the envi-ronment with high purity and chemical aggressive gas mixture at the 720-930 ^{0}C temperature. As exit parameter in this ACS serves the concentration of impurity introduced in the epitaxial layer by the alloying process at the growing of semiconductor structures subsequently utilized for applicative devices of solar radiation conversion, of electrical current rectifying, of electrical circuit release etc.

According to theory the indicators quality of adjustment process is provided concomitantly with the stability indicators and are determined by technological process requirements exclusively. Usually the quality of adjustment process is estimated by unitary transfer characteristic of the system at the action of a one step disturbance. The main indicators of adjustment quality are: adjustment time, overshooting, oscillation degree and stationary error.

For the technological process [2] an automatic adjustment system is indicated, which would provide a minimal stationary error (maximal degree of stability (MDS)) of vapor concentration of semiconductor alloying substance on sub-layer surface, situated in the growing zone of the reactor. This is needed to ensure the homogeneousness of the epitaxial layer grown as in radial as in grow direction. If the possibility of alloy concentration measurement during the technological process is not allowable, the system stability can be performed by controlling the vapor flux at the entry of reactor. This technical solution was achieved in [3]. But the technological processes, which takes place in the reactor during the grow of multi-layers epitaxial structures with the different semiconductor conductibility, determines other technical requirements referred to the adjustment time and transient overshooting of vapor flux at the entry in the reactor. The accomplishment of these requirements in ACS, elaborated and implemented in epitaxial equipment IEC-3/4R for gallium arsenide (GaAs), constitutes the content of this report.

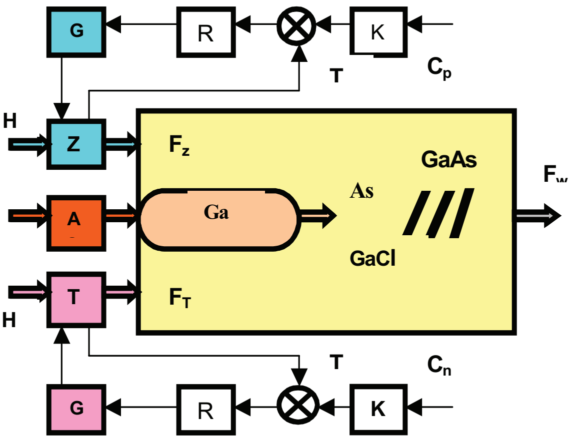

Fig. 1. Gas fluxes scheme in IEC–3-4R epitaxy installation.

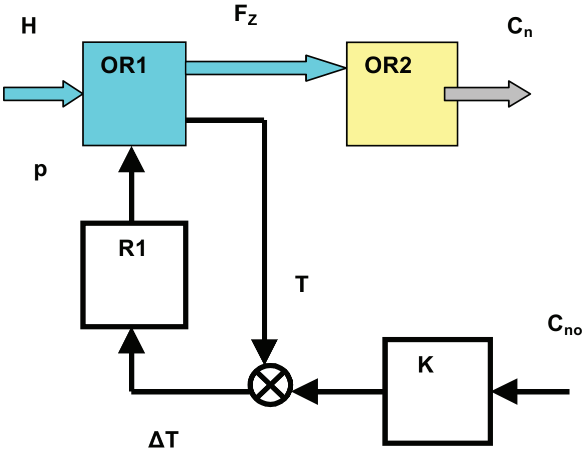

Fig. 2. Automation control system scheme of GaAs alloying process.

II. GROWTH OF STRUCTURES WITH EPITAXIAL LAIYERS

A. Technological process of GaAs epitaxy with reaction transport

The growth of semiconductor structures with multi-layers for different applications by utilizing the method with reaction transport in gas system $AsCl_3$-Ga-H_2 is produced in technological installation IEC-3/4R with quartz horizontal reactor at low pressure *(p=10-100 Pa)*. The principle scheme (staff) of gas fluxes is shown in Fig. 1. In the picture the simple arrow indicates the electrical signals and figurative arrows – gas fluxes.

The adjustment object represents the technological process, which is produced in the reactor with gas fluxes GaCl, As_2 Zn, Te, H_2. Some fluxes are generated in separate sources (Z and T) by the technologic sub-process of mixing the alloying substance vapor with the transport agent - hydrogen (H_2), but other fluxes are formed in the technological process with chemical reactions as can be $2AsCl_3 + 3H_2 = 6HCl + As_2$ in gallium source chamber or $2HCl + Ga = GaCl_2 + H_2$ etc. At the entry of the reactor the fluxes of gas are mixed by diffusion during their transport in axial direction of the reactor and form a total flux with a laminar dynamic, which moves with 0,45 cm/s of speed. In the growth zone they are deposited on semiconductor sub-layers in form of epitaxial layer GaAs:Zn or GaAs:Te and on technological bushing in the respective area of the reactor. Therefore this technological process forms an open system, which is required to be automated.

B. Technological process of GaAs alloying

Complexity of the GaAs growth technological process is demonstrated by the presence of many processes of different nature: chemical, thermal, gas-dynamics, which are activated in functioning regime of the integral process (purging blow, corrode, gallium saturation, verification layer growth, p-n junction structure growth with many layers etc.).

The automation of this complex process is divided in the sub-system of automatic adjustment.

Technological sub-process of semiconductor structure alloying is the most sensible at the product quality and responsible for charge carrier concentration in the epitaxial layer. He determines principal requires for the automation adjustment of F_Z and F_T gas fluxes generated in OR1 (Fig. 2.), but being controlled by the measurement of vapor sources temperature at the entry of reactor. The vapor fluxes have a value settled by the operator and a variable dynamics in the growth process of structures with many programmable layers. The ACS structure of F_Z and F_T formation process is presented in Fig. 2. Quality parameters of adjustment are determined from technological processes requirements, which are produced in reactor as opened control object OR2.

OR1 – first control object (vapor produce); OR2 – second control object (growth layers); R1 – vapor flux automat control; K – reference signal converter; H – hydrogen flux; F_n – vapor flux; C_n – impurity concentration in epitaxial layer; C_{no} – reference concentration; T – vapor generator temperature; P = saturated vapor pressure.

Concentration of GaAs charge carrier in dependence of alloying material temperature (tellurium or zinc) is experimentally established and shown in Fig. 3. This data serve as reference for the technologist at planning and adjusting ACS of the vapor with hydrogen flux mixing technological process.

The technological processes dynamics, which are produced in OR1 and OR2, are different. Production of vapor with hydrogen mixture in OR1, having a constant capacity (4,6 cm^3), needs to be maximized at the parameter of F_Z saturated vapor concentration in accordance with reference data of OR2 stationary exit parameter. There are two acceptable alternatives for filling the reactor capacity OR2 (V = 1385 cm^3) with vapor mixture during a period as brief as possible (30 cm : 0,45 cm/s = 67 s.): (i) the accomplishment of a programmed sub-system of vapor flux control by replacing the K reference converter with a programmer; or (ii) the accomplishment of a stabilization sub-system of control utilizing the overshooting parameter as acceleration element of vapor flux at the first stage, simultaneously providing maximum stability of rank (MSR) of impurity concentration in epitaxial

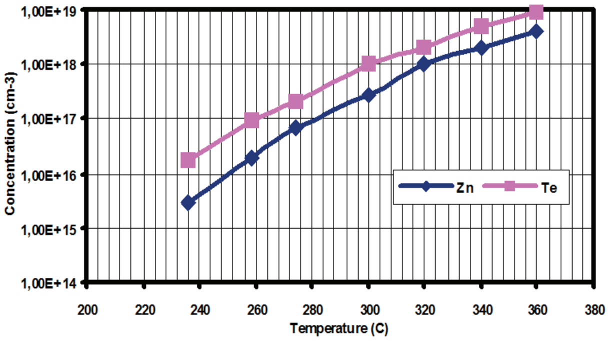

Fig. 3. Charge carrier concentration of GaAs in dependence with alloying substance temperature.

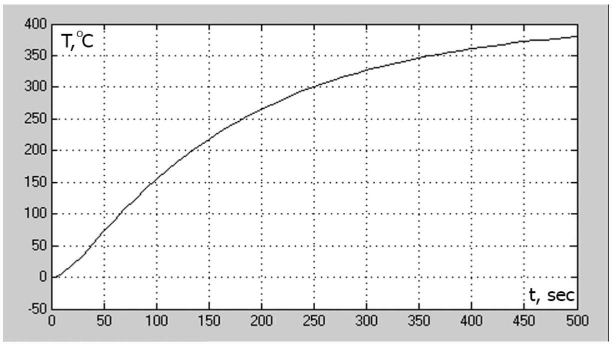

Fig. 4. The experimental curve of the heater process the alloying source OR1.

layer during the growth. The second alternative represents an interest for relative small constructive reactor (IEC-3/4R, d-50 cm) and is modeled in the present investigation.

Essential in this technological process is the abrupt interruption (breaking off) of F_Z vapor flux and introducing the other type of F_T vapor flux with the same dynamic characteristics in as brief as possible time in the same condition of hydrogen flux through respective alloying channels.

III. FORCEFUL OVERSHOOTING IN THE ALLOYNG PROCESS

A. Identification of the control object

The technology program provides the alloying of layers with tellurium or zinc with concentrations in the range of 10^{15} - $2\text{x}10^{18}$ cm^{-3} by setting the temperature of the heater to the alloying source in the range of 280-480 °C in concordance with references concentrations Fig. 3. For example, it was setted the source temperature to 410 °C. Following the experience it was obtained the experimental curve of the heater process the alloying source OR1 in the function of the time, Fig. 4. As can be seen from the graph the nominal power of the heater provides the output to the nominal regime over 11 minutes, which is not acceptable to provide a homogeneous conductivity in the axial direction of the growing the layer. It is necessary the impulse of energy for forcing the evaporation process. Based on these requirements, the transient process was identified using the software package ISIDORA.

Following the identification it was obtained the differential equation

$$a_0 y''(t) + a_1'(t) + a_0 y(t) = kx(t) \qquad (1)$$

From equation (1) results the following transfer function with identified parameters

$$H_F(s) = \frac{k}{a_0 s^2 + a_1 s + 1} = \frac{400}{43{,}63 s^2 + 17{,}5 s + 1} \qquad (2)$$

The characteristic equation of the control object is

$$A(s) = a_0 s^2 + a_1 s + 1$$

B. Synthesis algorithm of control system with imposed overshooting using the maximal stability degree method

As it was said the growing of GaAs epitaxial is the continuous process. Therefore in order to get the homogeneous layers it is necessary that the alloying source provides the flow of steam higher than the stationary value in the short time. Then the reactor will be filled with more quickly and the layers with different conductivity will have a sudden transition of the PN junction.

It was used the synthesis algorithm with imposed overshooting by the maximal stability degree method for tune the controller [4]. Based on this algorithm it was observed that the tuning parameters are in the dependency of: the parameters of transfer function, the maximal stability degree J of the designed system and at the imaginary parts ω_k of the complex roots of the characteristic equation:

$$b_j = f_j(k, a_0, \ldots, a_n, J, \omega_k); \; j = (1, \ldots, m) \qquad (3)$$

where J - maximal stability degree, $k, a_0, \ldots, a_n$ - the parameters of the control object, ω_k - the imaginary part of complex roots, m - the number of tuning parameters in the control law.

The algorithm of tuning controller is achieved by the following steps:

1. It is determined the transfer function of the closed loop system with selected controller.

2. It is obtained the characteristic equation of the closed loop system

$$A(p, b_j) = d_0 p^n + d_1 p^{n-1} + \ldots + d_{n-1} p + d_n = 0$$

3. Using the substitution $p_k = \pm j\omega_k - J$, the characteristic equation decomposes into n linear factors and presented in the following form

$$A(p) = d_0 \prod_{k=1}^{z} (p - j\omega_k + J)(p + j\omega_k + J) \prod^{r} (p + J) =$$
$$= q_0 p^n + q_1 p^{n-1} + \ldots + q_{n-1} p + q_n = 0$$

4. From the equality

$$d_i(a_i) = q_i(a_0, J, \omega_k), \; i = (n - m), \omega_k = 0$$

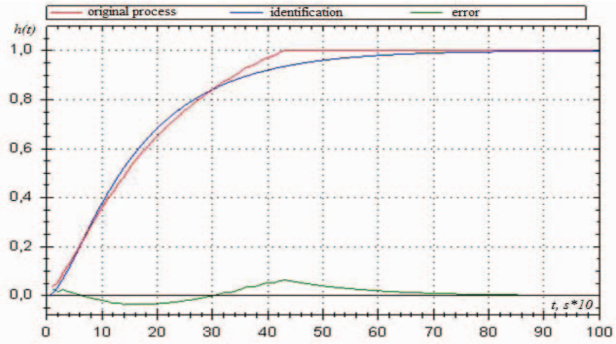

Fig. 5. Identification OR1 according to the method Orman-1.

after some transformations, it was obtained the expression for determining the maximal stability degree of the control system

$$J = f(a_0, a_i), i = (n-m)$$

where m - the number of the tuning parameters in the control law; a_i - the parameters of the control object.

5. Using the equalities

$$d_i(k, a_i, b_j) = q_i(a_0, J, \omega_k), i = ((n-(m-1)),...,n), j = 1,...,m$$

it is determined the expressions for calculating the tuning parameters

$$b_j = f_j(k, a_0, a_i, J, \omega_k);\ i = ((n-(m-1)),...,n),\ j = (1,...,m)$$

where the free parameters ω_k represent the imaginary parts of the roots of the characteristic equation of the control system.

6. In the dependence of the imposed overshooting σ% it is determined the value of imaginary component of the dominant root ω_k [4]:

$$\omega_k = \frac{p}{\ln\frac{(1,\quad 2,5)100}{\sigma\%}} J \qquad (4)$$

7. Calculation the value of the tuning parameters using the algebraic expressions obtained in the step 5.

C. Tuning controller to the identified model object using the Orman-1 method

In accordance with the exposed algorithm to the identified model object presented with transfer function (2), it was calculated the value of the maximal stability degree by the following relation

$$J = \frac{1{,}2a_1}{3a_0}$$

To the system it is required the overshooting equal with 20% and according to the equation (4) were determined the value of the imaginary part of the dominant root of the characteristic equation:

$$\omega_1 = \frac{pJ}{\ln\frac{200}{20\%}} = 0{,}22$$

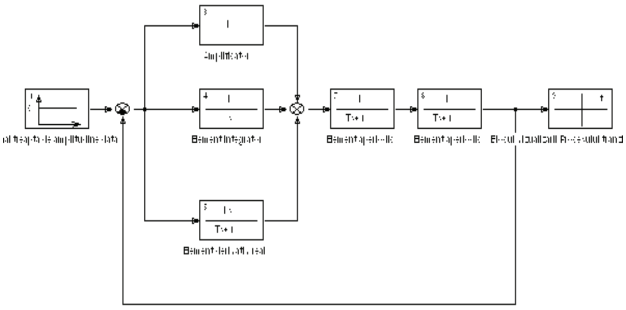

Fig. 6. Block diagram of the control system.

Based on these calculations were determined the following relations for the calculation the tuning parameters:

$$k_p = \frac{1}{k}[3a_0J^2 + a_0\omega_1^{\ 2} - 1] = 0.01115$$

$$k_i = \frac{1}{k}[a_0J^3 + a_0\omega_1^{\ 2}] = 0.0013$$

$$k_d = \frac{1}{k}[3a_0J - a_1] = 0.0086$$

The system was simulated in the software package KOPRAS. The obtained transient process is presented in the Fig. 7.

Surge characteristic obtained by simulation Fig. 7 with 20% of forced overshooting and damping degree close to the unity allows an indirect evaluation of the control quality parameters. The control quality is estimated by placing the first root of characteristic equation from imaginary axe α = 0.117, keeping the maximal degree of stability according to technological requirements. The degree of stability is related with control time t_r, minimized in accordance with technological requirements, by relation *α = ln n/*t_r, where *n* - ratio between initial swerve of control parameter and the same parameter at the expiration of calculated control time.

Mole concentration of zinc vapor at the reactor entry is calculated for all source surfaces in function of the temperature and is presented in Fig. 8. By calculation was checked up the vapor quantity in the reactor during 15 seconds of 20% transient overshooting at the temperature from 410 °C to 492 °C. This vapor flux arrives to the growth zone in the control time of controller.

IV. CONCLUSIONS

Alloying process ACS elaboration of GaAs epitaxial layers obtained at the IEC-3/4R equipment by reaction transport technology in the gas system Ga-$AsCl_3$ -H_2, permits the adjustment of automate control quality of alloying (Zn/Te) vapour concentration in the growth zone of the reactor by indirect methods. Vapour flux produced in the alloying source chamber and transported by hydrogen in the reactor is coming to the growth zone with 2-6 of min delay because the reactor capacity is better ($V_r >> V_z$) than the alloying chamber capacity.

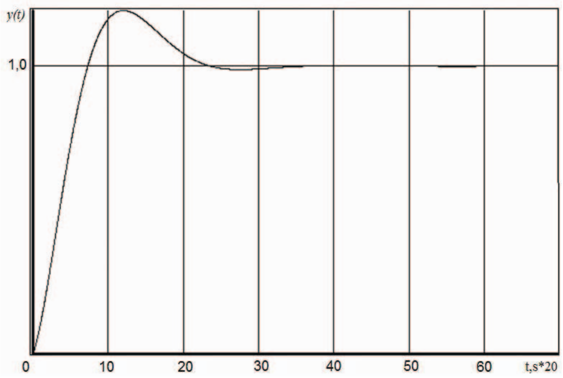

Fig.7. Transient process of the control system.

The optimization parameters in the technological process are the time of filling the reactor with vapour and the time of the reactor evacuation after interruption of the vapour flux. This time is directly related with the vapor source efficiency and can be minimized by a forced overshooting of alloy source temperature.

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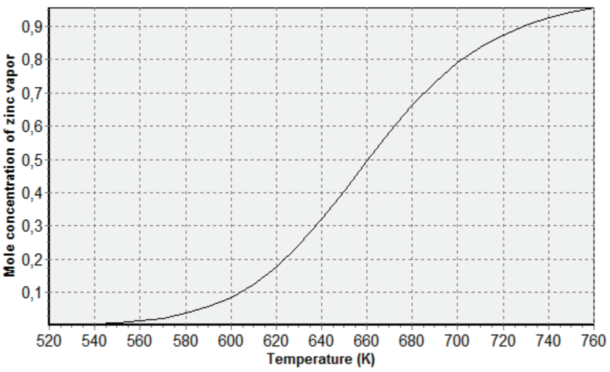

Fig. 8. Dependency of Zn output vapors concentration of temperature.

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