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STUDY OF MANUFACTURING DEFECTS IN THE TECHNOLOGY OF MANUFACTURING MOEMS SEMICONDUCTOR SUBSTRATES FOR TECHNICAL AUTOMATION MEANS

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ABSTRACT

Today, in the context of the widespread use of digital, network and intelligent technologies, and the continuous development of integrated production innovations, major and profound changes are taking place in the philosophy of modern industry development. Such changes set manufacturers the task of automating production process control in real time, which involves creating a single enterprise information space that links together the technological and business levels of enterprise management, while solving many of the most important tasks for an industrial enterprise.

Integration of the cyber component allows automating the management of production processes through the use of intelligent mechatronic modules, expert systems and large data sets for production forecasting. In this context, a person controls processes at the physical level through a cybernetic system. At the same time, this system with minimal human involvement allows: automatic control of the vehicle at the physical level, analysis and decision-making in real time. Systems of this type are multilevel. At the lower level, accurate and reliable systems such as microelectromechanical and micro-optomechanical are used. They collect, process, and transmit information in the control of technological systems. The accuracy and durability of MEMS and MOEMS depends on the technology of their manufacture.

The aim of this work is to increase the efficiency of control by using proximity sensors based on MEMS and MOEMS as part of technical automation means.

Keywords: technical automation means, defect, technological process, MEMS, MOEMS, substrate, diffusion, defect engineering.

1. INTRODUCTION

Today, in the context of the widespread use of digital, network and intelligent technologies, and the continuous development of integrated production innovations, major and profound changes are taking place in the philosophy of modern industry development. Such changes set manufacturers the task of automating production process control in real time, which involves creating a single enterprise information space that links together the technological and business levels of enterprise management, while solving many of the most important tasks for an industrial enterprise.

The amount of information that needs to be received and promptly processed to form effective control influences in modern control systems for complex production facilities has grown so much that with the development of network technologies, the control architecture is changing, control levels are being combined, sensor information can be directly transferred to cloud services, and production planning services process the necessary data in real time.

At the present stage, all sensors are based on the so-called MEMS technology (MEMS mycoelectromechanical systems), which in turn have a wide range and diversity.

If we consider the mechanisms of information processing and transmission in the management of technological systems at modern enterprises, we can determine that MEMS (microelectromechanical systems) and MOEMS (microoptomechanical systems) are the most common.

Currently, more than twenty technological methods and directions for the manufacture of MEMS and MOEMS products based on silicon structures are known [1-3].

The control and testing operations that are part of modern technological processes cannot give a complete guarantee of the absence of defects in the production of this type of components and their behavior over time, taking into account the operating conditions [4-7].

2023, 2(2), pp. 247-253 DOI: 10.5281/zenodo.10370530

Most of the defects arise precisely because of the defects and (or) the presence of impurities in the starting materials of substrates or substrate sublayers of functional MOEMS components and during the technological process of their manufacture [7-8].

Therefore, it was decided to consider defects in the substrates of the layers and sublayers of the functional MOEMS component as the main and primary source of defects in the MOEMS component as a whole.

The problem arises from the fact that at the stage of production of initial materials, it is unlikely that it is possible to track the defectiveness of structures and the dependence of physical and technological parameters that directly affect the quality and compliance of the output characteristics of MEMS components, a special limitation is imposed by the factor of the kinetics of degradation processes in materials during and conditions of operation of the product.

Nevertheless, the main reason for the limited resource characteristics of functional MOEMS components is manufacturing defects that develop over time during the operation of the MEMS.

In this regard, there is an "open" scientific and practical task of predicting and controlling the defect formation of layers and sublayers of functional components of MOEMS, which is solved by controlling the operating parameters, the development of defects inherent in the production, which in turn do not always worsen the parameters of microsystems [9-12], but on the contrary, over time, even with the right approaches and certain operating conditions, can improve [10-12].

2. PREDICTION AND MANAGEMENT OF TECHNOLOGICAL DEFECTS IN THE MANUFACTURE OF SEMICONDUCTOR SYSTEMS

It is the prediction and management of technological defects in the manufacture of semiconductor systems that is a rather promising direction of development in the development of technological processes for the manufacture of MEMS and MOEMS.

The possibility of control has become the basis for the development of a promising scientific direction in the technologies of manufacturing semiconductors, materials, and electronic devices - defect engineering [12], which is based on the management and prediction of defect formation processes.

Microelectromechanical systems are formed by combining mechanical elements, sensors, and electronics on a common semiconductor substrate using micro- and nanofabrication technologies [3, 4]. The methods used in the manufacturing processes of MEMS can be classified into one of the following classes

- volumetric processing to obtain a high aspect ratio

- surface treatment;

- mixed technology that uses the first two;

- hybrid technology with the assembly of mechanical and electronic parts at the level of atomic and molecular splicing;

- others (fiber, micromechanical processing, bulk polymer);

- multilayer film structures [3].

There are three types of the most common defects formed on semiconductors:

- surface: formed due to various types of mechanical processing, such as blade cutting, grinding, polishing, the main way to eliminate them is to flatten the surface layer of the silicon substrate;

- corner defects: due to anisotropic etching, which causes crack initiation - the main way to eliminate them is to use isotropic etching, which rounds the edges of the substrate, which virtually eliminates (minimizes) corner defects;

- volumetric: arise due to heat treatment and lead to internal stresses, which, in combination with edge, surface and volumetric imperfections of the structure, can lead to stress concentration and subsequent splitting of the substrate in the plane.

If we consider the defect formation of such components through the prism of physicochemical transformations and reactions, we can distinguish several main mechanisms of manufacturing defects in functional components of

2023, 2(2), pp. 247-253 DOI: 10.5281/zenodo.10370530

MOEMS, the development of which is associated with the transformation of the micro- and macrostructure of the starting materials that occur during the production and operation of functional components of MOEMS.

1. The diffusion of layers and sublayers of functional MOEMS components can be represented using the second Fick's law: for one-dimensional diffusion (1) or diffusion through a film (2):

$$\frac{dV}{dt} = D\frac{d^2V}{dx^2}, \quad (1)$$

$$\frac{dV}{dt} = D\frac{\Delta V}{y}, \quad (2)$$

where $D-$ diffusion coefficient;

$V-$ concentration of the diffusion component;

$y-$ film thickness.

2. Chemical corrosion of layers and sublayers of functional components of MOEMS can be represented as (3), and in the presence of protective films (4):

$$\frac{dV}{dt} = V_0 e^{-\frac{E}{RT}}, \quad (3)$$

$$\frac{dV}{dt} = \frac{k_d k_p}{k_d + k_p h_0} V_0, \quad (4)$$

where E – activation energy of the molecules involved in the reaction;

$k_p -$ chemical reaction speed constant;

$V_0 -$ concentration of the reagent on the outer surface at the boundary with the gas phase;

$h_0 -$ coating thickness;

$k_d -$ corrosion diffusion coefficient.

3. Electrical corrosion can be expressed as the amount of material worn away (5) and the depth of wear (6):

$$V_Э = \gamma_{(-)} Q, \quad (5)$$

$$h = \frac{\gamma_{(-)}}{\rho}\frac{Q}{s_0} = \frac{\gamma_{(-)}}{\rho s_0}\int_0^t i\,dt = \frac{\gamma_{(-)}}{\rho s_0} I_{CP} t. \quad (6)$$

where $\gamma_{(-)} -$ erosion coefficient;

$Q-$ quantity of electricity;

ρ – specific weight;

$s_0 -$ area of worn part of the surface;

$I_{CP} -$ average current value;

$t-$ time of current action.

2023, 2(2), pp. 247-253 DOI: 10.5281/zenodo.10370530

4. The evaporation of the material (process rate) can be expressed as (7):

$$V' = {\frac{kp}{\sqrt{2\pi R}}} \Big/ {p\sqrt{\frac{M}{T}}}, \qquad (7)$$

where $M -$ molecular weight of the material to be evaporated;

$p -$ pressure;

$R -$ gas consyant;

$T -$ absolute temperature [12].

Thus, during the implementation of technological processes, the defects that have arisen further develop in accordance with the objective laws of change in the micro- and macrostructure of the materials that make up the elements and devices of MEMS and MOEMS.

Considering different materials and processes of manufacturing defects development, analyzing and generalizing the mechanism of the processes, it can be concluded that there are three main types of the above changes: diffusion of components, corrosion (chemical, electrical, electrochemical) and evaporation.

The analysis of the capabilities of defect detection tools and data on the causes of MEMS and MOEMS failures shows that a significant part of defects may not be detected. Therefore, attention is paid to the prediction of parametric failures during production testing and maintenance, and as a result, decisions are made on the technical condition and production technology of devices [12-7].

Modern forecasting methods are based on functional analysis, series theory, extrapolation and interpolation theory, probability theory and mathematical statistics, theory of random functions and random processes, correlation and spectral analysis, and pattern recognition theory.

When displaying the time dependence of parameters, linear and quadratic models are used. Paper [12] shows that increasing the order of the model above the second order does not significantly increase the accuracy of the forecast, but significantly complicates the calculation procedures.

In the framework of forecasting using the theory of recognition], it is customary to distinguish in the n-dimensional space the regions that correspond to certain degrees of performance of MEMS and MOEMS, and to determine the limit of the acceptable level of performance.

Much attention is paid to the quality of the forecast, i.e., the set of such characteristics of the forecast, which together make it effective, useful in management, provide a reliable description of the object for a certain perspective and the possibility of reliable use of the forecast results for the management procedure.

Forecast results are always associated with certain management procedures, and the quality of the forecast can be assessed in terms of the needs of the management itself and its sensitivity to possible forecasting errors.

The main directions for a reasonable determination of the forecast quality should be sought in the assessment of uncertainty [13-18] that a particular description of an object carries.

The quality of the forecast depends primarily on the completeness and quality of the description of the object itself; the forecasting procedure has a specific component - "time" and therefore descriptive topological characteristics are supplemented by dynamic ones [19].

Assessment of forecasting results should be carried out based on the consideration of internal processes and external influences on the MEMS. Obtaining forecast results under the influence of variable external factors increases the efficiency of the forecast, making it an effective tool for managing the production of MEMS and MOEMS.

The currently existing verification methods mostly operate only with statistical procedures, which are reduced to estimating confidence intervals for the results under consideration.

This involves two types of errors: errors determined by information or description of the object, and errors of the forecasting method itself [20]. Errors of the first type are quite easy to formalize and can be calculated by statistical methods. Analysis of the initial information involves identifying a set of statistical indicators, including determining the type of distribution. Many statistical calculations and criteria are valid only for the normal distribution law, otherwise the estimates are ineffective.

Methods to improve efficiency include: identifying abnormal observations, separating non-periodic components, identifying abrupt changes in the trend of the process under study, identifying variations in the process under study, identifying variations in the indicator under study, and its frequency.

When making forecasts, one should always evaluate and find the optimal match between the information and the method used to make the forecast. There is a need to develop methods for improving the quality [21] of the forecast based on the description of objects and the use of some new concepts for forecasting: stability, inertia, connectivity, complexity, appearance and functional integrity of the object, accuracy and completeness of the description, and decision-making risk.

Thus, the concept of inertia characterizes the resistance of an object in time to changes in its own trajectory under the influence of the external environment; stability implies a certain preference for development directions in time, the choice of any specific trajectories by the object, both in the space of the indicators under consideration and in time.

For adequate assessment, forecasting, prediction and management of MEMS and MOEMS defects, it is necessary to thoroughly study the physical and chemical processes underlying their production, possible variable conditions of their operation and, based on the information obtained, after careful analysis, develop mathematical models that would provide insight and explanation of the occurrence and development of production defects over time.

CONCLUSIONS

In the context of modern production approaches, the level at which information about the production parameters of technological processes is obtained is the lower level, the operation of which is ensured by technical means of automation.

Such means include precision sensors and actuators. The quality, accuracy, and reliability of information obtained directly at production sites depends on the production technology of such systems. The failures and processes that occur depend on the quality and defectiveness of technical automation means, such as MEMS and MOEMS.

It is shown that modeling and displaying the processes of production defects development to predict parametric failures, change and adjust the technological processes of MEMS and MOEMS production is an urgent scientific and practical task that can be solved on the basis of defect engineering.

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