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REGULAR ARTICLE

Microwave Photomodulation Method for Noninvasive Analysis of Doping Profiles in Inhomogeneous Semiconductor Structures

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A non-destructive microwave method for testing inhomogeneously doped semiconductor structures is presented, enabling high-precision reconstruction of arbitrary specific conductivity profiles along the sample thickness. The method is based on analyzing variations in the quality factor of a microwave resonator under illumination of the sample with light of variable wavelength. A mathematical model is proposed that incorporates sample discretization along its thickness, the solution of the continuity equation for charge carriers, and the characteristic equation of the resonant system. It is shown that the probing depth is determined by the absorption coefficient, which depends on the wavelength of the incident optical radiation. The developed approach provides high spatial resolution and measurement accuracy, making it a valuable tool for quality control of materials in advanced microelectronic technologies.

Keywords: Microwave diagnostics, Non-destructive testing, Semiconductor structures, Inhomogeneous doping, Specific conductivity profile, Quality factor, Optical illumination, Resonator, Absorption coefficient.

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1. INTRODUCTION

Manufacturers of modern semiconductor device technologies, while optimizing production processes, collect data on die parameters across the entire surface of the substrate at each stage of fabrication. This in-formation is recorded in the form of a wafer map – a graphical representation of the wafer that serves to visualize and classify each individual die based on test results. Subsequently, the wafer map is used as a tool for defect localization, statistical process control, and decision-making regarding subsequent manufacturing operations. An example of a typical wafer map is shown in Fig. 1.

A system of quality indicators for semiconductor materials, including elementary semiconductors (silicon, germanium) and their compounds (e.g., AIIBV type), manufactured as both homogeneous (ingots, wafers) and complex-inhomogeneous (epitaxial and diffusion structures), is characterized by the following parameters and properties:

– specific electrical resistivity;
– charge carrier mobility;
– free charge carrier concentration;
– minority carrier lifetime and surface recombination velocity;
– substrate and epitaxial layer thickness;
– doping profile.

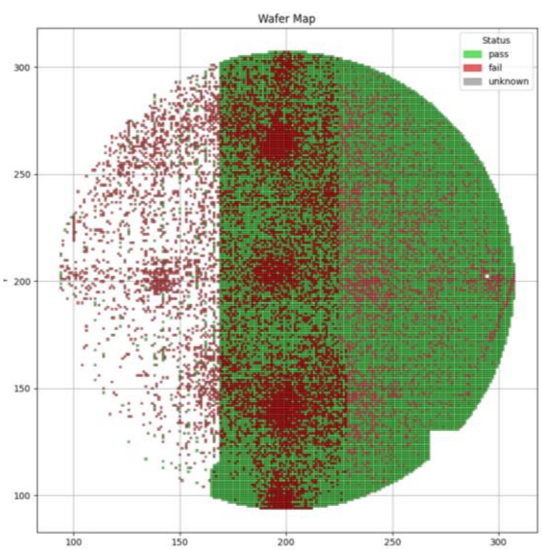

Fig. 1 – An example of a wafer map from ATX Group company

During the design of semiconductor devices and integrated circuits, appropriate material parameters are selected based on theoretical calculations and experimental data. In prototype device testing during pilot production, material requirements are further refined, as each type of

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device or integrated circuit has optimal semiconductor parameters (e.g., Si, Ge, GaAs, etc.) corresponding to the desired device characteristics. The reproducibility and yield of acceptable products are directly related to the quality and variability of the semiconductor material parameters.

Therefore, semiconductor materials used in the manufacturing of devices and integrated circuits must meet the following general requirements [1]:

– materials must not contain significant amounts of foreign impurities relative to the specified dopants, as such contaminants may cause uncontrolled and non-reproducible changes in electrophysical properties during thermal processing;

– materials must exhibit reproducible, specified, and homogeneously distributed levels of structural defects (dislocations, vacancies);

– crystals should be free of defects such as inclusions and microcracks;

– ingots should be free of significant mechanical stresses.

Violations of these requirements can lead to increased defect rates during wafer slicing, grinding, etching, p-n junction formation, photolithography, and related processes.

Traditional contact-based probe methods are most widely used for quality control during material acceptance, delivery, and incoming inspection. Non-destructive methods are primarily employed in the study of material properties, process development, and technological control [2].

One important direction in the non-destructive and contactless investigation of material and structural properties is the use of microwave (MW) methods and tools. These methods allow for the examination of material characteristics without direct contact, which is crucial for preserving sample integrity and avoiding any influence on the investigated material.

Microwave diagnostic methods for material parameters and characteristics are typically classified into two categories: non-resonant and resonant. Non-resonant methods are usually employed to determine property dependencies over a frequency range, while resonant methods aim to measure precise values of material parameters (e.g., dielectric permittivity and loss tangent) at specific frequencies or discrete frequency points [3,4].

In non-resonant methods, material properties are primarily derived from impedance and wave propagation characteristics in the material. These can be implemented using reflection or transmission/reflection techniques. In the former, properties are determined from reflection off the sample; in the latter, from both reflection and transmission through the sample. These methods can be applied using various types of trans-mission lines, such as coaxial lines, hollow metallic or dielectric waveguides, or microstrip lines.

In resonant methods, material parameters and properties are derived from their influence on the resonant frequency and quality factor of the measurement transducer. These methods utilize different types of microwave resonators, including rectangular, cylindrical, coaxial, and microstrip resonators.

Thus, in today's context of high standards, obtaining high-quality materials requires the application of more efficient control methods. Ensuring the quality of materials can be optimally achieved through contact-less, non-destructive methods, which allow for accurate parameter monitoring without damaging the material. This is particularly important in light of modern reliability and performance requirements across various industries, including electronics, manufacturing, and medicine. Such non-destructive techniques enable timely detection and elimination of potential defects or in-consistencies, thereby contributing to improved material quality and durability.

This study investigates the possibility of controlling the depth profile of specific conductivity in inhomogeneously doped semiconductor structures by analyzing the measured quality factor of a microwave resonator operating in the H_{012} mode, with the sample placed inside the resonator and illuminated by light of varying wavelength.

2. RESULTS AND DISCUSSION

Information about an arbitrary doping profile can be obtained by analyzing the output signal of a microwave resonator-based measurement transducer (RMT) loaded with an inhomogeneously doped sample. This is done while simultaneously illuminating the sample with light in the intrinsic photosensitivity range of the semiconductor and varying the relative position of the sample and the electromagnetic field of one of the fundamental resonant modes of the microwave resonator. The wavelength of the incident radiation—and, accordingly, its absorption coefficient in the material—determines the depth within which the sample is probed. The relative movement of the sample with respect to the field enables the optimization of measurement conditions for acquiring the desired out-put signal [5].

The solution of this problem is implemented using numerical methods, specifically through the discretization of the sample along its thickness. In this approach, the structure of the sample is conditionally divided into a certain number of individual layers, each assumed to be homogeneous in its physical, electrical, and dielectric properties (see Fig. 2a). This discretization significantly simplifies the mathematical modeling of a complex inhomogeneously doped semiconductor structure by approximating it as an equivalent multilayer system with well-defined parameters for each layer [6].

The number of layers selected represents a critical parameter of the model, as it directly determines the spatial (depth) resolution of the method. A greater number of layers allows for a more accurate reconstruction of the variation of physical properties within the sample, including changes in specific conductivity, dielectric permittivity, and other characteristics. However, increasing the number of layers also leads to higher computational complexity, requiring greater computational effort and, consequently, more powerful hardware resources. Therefore, a balance must be achieved during the modeling process between the desired accuracy and the acceptable level of computational load.

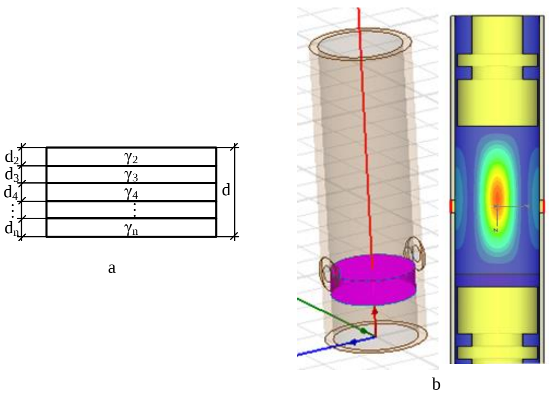


Fig. 2 – Microwave cylindrical resonator: (a) division of the sample into layers; (b) schematic representation of a composite RMT with two tuning plungers and internal placement of the sample

As a resonant measuring transducer (RMT), it is reasonable to select a microwave cylindrical resonator operating in the H_{012} mode (see Fig. 2b) [6, 7]. Structurally, the resonator consists of two coaxially aligned sections and is equipped with two tuning plungers. The presence of the tuning plungers allows for adjustment of the sample's position relative to the spatial distribution of the electromagnetic field inside the resonator, thereby controlling the degree of sample coupling with the resonator field ($\beta_0 H$). This approach makes it possible to experimentally determine the optimal sample position at which the output measurement signal of the resonant system reaches its maximum value, which is crucial for enhancing both the sensitivity and accuracy of the measurement process.

For a detailed mathematical description of such a system and for determining the interrelations between its main parameters, the so-called characteristic equation (1) is typically used. This equation enables the formalization of the physical processes within the system and allows for a quantitative assessment of its key characteristics.

$$th(\gamma_1 z_0) = -\frac{\gamma_1}{\gamma_2}\cdot\frac{th(\gamma_2 d_2)+\frac{\gamma_2}{\gamma_3}\cdot\dfrac{th(\gamma_3 d_3)+\frac{\gamma_3}{\gamma_4}\cdot\frac{th(\gamma_4 d_4)+\cdots}{1+}}{1+\frac{\gamma_3}{\gamma_4}\cdot th(\gamma_3 d_3)\cdot\frac{th(\gamma_4 d_4)+\cdots}{1+\cdots}}}{1+\frac{\gamma_2}{\gamma_3}\cdot th(\gamma_2 d_2)\cdot\dfrac{th(\gamma_3 d_3)+\frac{\gamma_3}{\gamma_4}\cdot\frac{th(\gamma_4 d_4)+\cdots}{1+\cdots}}{1+\frac{\gamma_3}{\gamma_4}\cdot th(\gamma_3 d_3)\cdot\frac{th(\gamma_4 d_4)+\cdots}{1+\cdots}}}, \quad (1)$$

where γ_1, γ_2, γ_3 and γ_4 are complex propagation constants, and z_1, d_2, d_3, and d_4 are the longitudinal dimensions of the corresponding regions.

The expressions for the propagation constants γ_i have the following general form:

$$\gamma_i = \sqrt{-\varpi^2\cdot\mu_0\cdot\varepsilon_i^* - \left(\frac{\nu_{01}}{R}\right)^2},$$

where $\varpi = \omega' + j\cdot\omega''$ is the complex frequency, $\varepsilon_i^* = \varepsilon_0\cdot\varepsilon_i\cdot(1+j\cdot tg(\sigma_i))$ is the complex dielectric permittivity of the i-th layer, $tg\sigma_i$ is the loss tangent of the i-th layer, ε_i is the real part of the dielectric permittivity of the i-th layer, ν_{01} is the first root of the zero-order Bessel function, and R is the radius of the resonator.

The numerical solution of equation (1) is performed with respect to the complex frequency. It is assumed that the parameters of the sample are predefined and known in advance. During the computation, both the real and imaginary components of the complex frequency are determined, corresponding to the resonant frequency and energy losses in the system, respectively. Based on the obtained values, the quality factor of the resonator containing the sample is calculated using the appropriate relation.

$$Q = \frac{Q_0\cdot\omega'}{2\cdot Q_0\cdot\omega'' + \omega'}$$

where Q_0 is the intrinsic quality factor of the resonator.

It is assumed that the penetration depth of radiation into the sample is inversely proportional to the absorption coefficient α. In other words, as the absorption coefficient increases, the effective depth to which the radiation propagates within the material decreases. Additionally, the absorption within each individual layer of the sample is considered to be uniform. This assumption simplifies the mathematical model and allows for a more focused analysis of the influence of the material's optical properties on the excitation depth.

To obtain information about the electrophysical parameters of an individual layer within a non-uniformly doped semiconductor sample composed of several layers with differing properties, it is necessary to perform mathematical modeling of the processes occurring under optical illumination. One of the key steps in such modeling is solving the stationary one-dimensional continuity equation (e.g., for holes), which describes the spatial distribution of charge carriers under steady-state or harmonically modulated illumination. It is assumed that monochromatic radiation with a fixed wavelength penetrates the sample to a depth inversely proportional to the absorption coefficient α, and that the absorption within each individual layer is spatially uniform. Under these assumptions, the continuity equation takes the form:

$$\frac{d^2\Delta p}{dx^2} - \frac{\Delta p}{D_p\tau_p} + \frac{g_0(\lambda)}{D_p}\exp(-\alpha(\lambda)\cdot x) = 0 \qquad (2)$$

where Δp is the excess hole concentration, D_p is the diffusion coefficient, and $g_0(\lambda)$ is the charge carrier generation rate.

The expression for the rate of charge carrier generation in the general case of a sample with arbitrary finite thickness is given by [8]:

$$g_0(\lambda) = \frac{\alpha(\lambda)\cdot\beta\cdot I_0(1-R)}{h\cdot\nu\cdot[1-R^2\cdot\exp(-2\cdot\alpha(\lambda)\cdot d)]}\cdot[\exp(-\alpha(\lambda)\cdot d)+R\cdot\exp[-\alpha(\lambda)(2d-x)]], \quad (3)$$

where β quantum efficiency coefficient, I_0 incident light intensity, R reflection coefficient of the radiation from the sample surface.

Under the condition of uniform radiation absorption in the sample ($\alpha x \le 1$), the charge carrier pair generation rate takes the form:

$$g_0(\lambda) = \frac{\alpha(\lambda)\cdot\beta\cdot I_0}{h\cdot\nu}$$

To solve equation (2), it is essential to specify appropriate boundary conditions at the sample surfaces. These conditions determine the nature of recombination processes and significantly influence the spatial behavior of charge carriers near the material interfaces. The boundary conditions must account for the surface recombination efficiency and the presence of passivation layers, as well as other physical factors such as electric fields, crystalline lattice defects, interfacial transitions, surface energy level variations, and thermal fluctuations. All of these phenomena can substantially alter the overall charge transport behavior within the system. Therefore, the precise formulation of boundary conditions is a necessary prerequisite for ac-curate mathematical modeling of the physical processes occurring in the studied structure. The surface recombination velocity of nonequilibrium charge carriers (S) plays a critical role in the overall charge transport mechanism in a semiconductor and can significantly affect the performance of devices based on optoelectronic or photosensitive effects. In our calculations, we will use boundary conditions that consider only surface recombination processes:

$$D_p\frac{d\Delta p}{dx}\Big|_{x=0} = s\Delta p(0)$$

$$-D_p\frac{d\Delta p}{dx}\Big|_{x=d} = s\Delta p(d)$$

The general solution of equation (2) is given by:

$$\Delta p = \frac{g_0(\lambda)\cdot\tau}{1-\alpha^2L^2}\cdot\left(A\cdot\exp\left(\frac{x}{L}\right)+B\cdot\exp\left(-\frac{x}{L}\right)+\exp(-\beta\cdot x)\right), \quad (4)$$

where

$$A = \frac{(S-\alpha(\lambda)\cdot D)\cdot\left(\frac{D}{L}+S\right)\cdot\exp(-\alpha(\lambda)\cdot d)+(S+\alpha(\lambda)\cdot D)\cdot\left(\frac{D}{L}-S\right)\cdot\exp\left(-\frac{d}{L}\right)}{\left(\frac{D}{L}-S\right)^2\cdot\exp\left(-\frac{d}{L}\right)-\left(\frac{D}{L}+S\right)^2\cdot\exp\left(\frac{d}{L}\right)}; \quad (5)$$

$$B = \frac{(S-\alpha(\lambda)\cdot D)\cdot\left(\frac{D}{L}-S\right)\cdot\exp(-\alpha(\lambda)\cdot d)+(S+\alpha(\lambda)\cdot D)\cdot\left(\frac{D}{L}+S\right)\cdot\exp\left(\frac{d}{L}\right)}{\left(\frac{D}{L}-S\right)^2\cdot\exp\left(-\frac{d}{L}\right)-\left(\frac{D}{L}+S\right)^2\cdot\exp\left(\frac{d}{L}\right)}; \quad (6)$$

$$L = \sqrt{D\tau}. \quad (7)$$

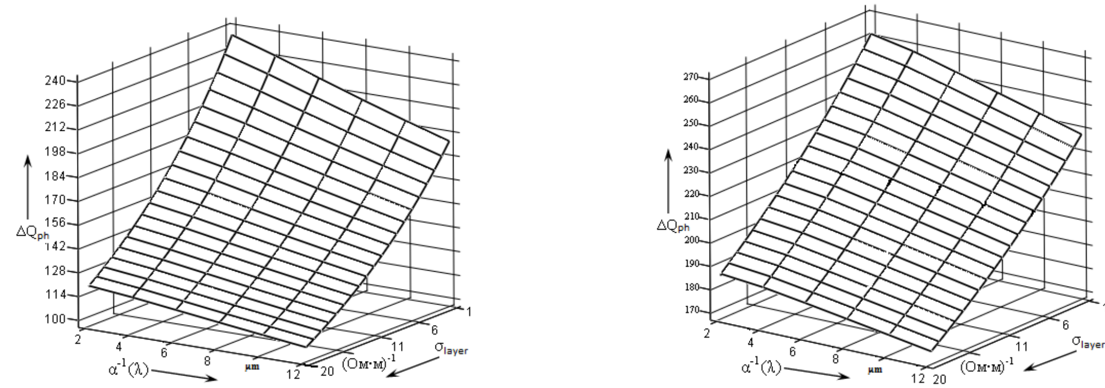
The total number of charge carriers in a layer of thickness d is determined by integrating equation (4), and after transformations, the following expression is obtained:

$$\Delta P = \frac{g_0(\lambda)\cdot\tau}{\alpha(\lambda)}\cdot\frac{1-\exp(-\alpha(\lambda)\cdot d)}{1+\frac{S\cdot\tau}{L}\cdot cth\left(\frac{d}{2\cdot L}\right)}\cdot\left[1+\frac{S\cdot L}{D}\cdot\frac{\left[cth\left(\frac{d}{2\cdot L}\right)-\alpha(\lambda)\cdot L\cdot cth\left(\frac{\alpha(\lambda)\cdot d}{2}\right)\right]}{1-\alpha(\lambda)^2\cdot L^2}\right]. \quad (8)$$

By solving equation (2) in conjunction with the characteristic equation of the resonator (1), one can derive a system of relationships that enables the calculation of the specific conductivity of an individual layer of the sample, provided its thickness is known. This approach allows for the analytical determination of the electrophysical parameters of layered structures and plays a significant role in the study of inhomogeneous semiconductor materials. As the measurement signal containing information about the photoconductivity of the sample, the difference between the quality factors of the resonator with the sample in the absence of optical illumination (in the dark Q_d) and under illumination (Q_{il}) is used, defined as $\Delta Q_{ph} = Q_d - Q_{il}$. Thus, the difference in quality factors serves as a measure of the changes in the sample's conductivity caused by the photogeneration of charge carriers, i.e., the photoconductivity signal, which is detected using a microwave shift technique.

Fig. 3 presents a representative set of calibration dependencies that establish a quantitative relationship between the photoconductivity response and the depth-resolved specific conductivity within the semiconductor material. These calibration curves constitute the methodological foundation for reconstructing the spatial profile of electrical conductivity across the thickness of a spatially inhomogeneously doped semiconductor structure, thereby facilitating a systematic layer-by-layer evaluation of its internal electrophysical parameters.

The measurement procedure can be carried out as follows. The sample, as shown in Fig. 2b, is placed inside the resonator. Using tuning plungers, the coupling level $\beta_0 H$ is adjusted to a point at which the photoconductivity signal reaches its maximum. The photoconductivity response ΔQ_{ph} is measured at the shortest available wavelength, and the specific conductivity of the first layer is determined using the calibration curves. Then, the wavelength is increased, the specific conductivity of the next layer is measured, and so on. The penetration depth of the radiation is determined by the ratio $1/\alpha(\lambda)$, where $\alpha(\lambda)$ is the absorption coefficient at the corresponding wavelength. The choice of a specific calibration characteristic is determined by the sample thickness and the extent of its inclusion in the microwave field of the resonator.



a b

Fig. 3 – Calibration characteristics for determining the specific conductivity distribution profile at $d = 112$ μm, $\beta_0 H = 0.3$ (a) and $d = 350$ μm, $\beta_0 H = 0.13$

Thus, by analyzing the dependence of ΔQ_{ph} on the wavelength of the incident radiation, it is possible to obtain the depth profile of the specific conductivity of an inhomogeneously doped semiconductor structure.

3. CONCLUSION

The proposed microwave non-destructive testing method for spatially inhomogeneously doped semiconductor structures enables accurate reconstruction of arbitrary specific conductivity profiles along the sample thickness. The method's effectiveness is attributed to its high sensitivity to variations in the material's electrophysical properties, particularly conductivity at different depths. The spatial resolution and overall accuracy are primarily determined by the magnitude of the wavelength shift of the incident electromagnetic radiation in successive measurements, as well as by the spectral stability, noise performance, and frequency range of the measurement system.

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Мікрохвильовий фотомодуляційний метод для неінвазивного аналізу профілів легування в неоднорідних напівпровідникових структурах

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Представлено неруйнівний мікрохвильовий метод контролю неоднорідно легованих напівпровідникових структур, який дає змогу з високою точністю відновлювати довільний профіль розподілу питомої електропровідності вздовж товщини зразка. Метод ґрунтується на аналізі змін добротності мікрохвильового резонатора під час опромінення зразка світлом змінної довжини хвилі. Запропоновано математичну модель, що включає дискретизацію зразка за товщиною, розв'язання рівняння неперервності для носіїв заряду та характеристичного рівняння резонансної системи. Показано, що глибина зондованого шару визначається коефіцієнтом поглинання, який залежить від довжини хвилі падаючого оптичного випромінювання. Розроблений підхід забезпечує високу просторову роздільну здатність і точність вимірювань, що робить його ефективним інструментом для контролю якості матеріалів у сучасних мікроелектронних технологіях.

Ключові слова: Мікрохвильова діагностика, Неруйнівний контроль, Напівпровідникові структури, Неоднорідне легування, Профіль питомої провідності, Добротність, Оптичне опромінення, Резонатор, Коефіцієнт поглинання.