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Properties of SiO_2-GaAs and Au-Ti-SiO_2-GaAs structures used in production of transmission lines

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Abstract. We investigated electrophysical properties of the SiO_2-GaAs and Au-Ti-SiO_2-GaAs structures that are used in technological process when manufacturing transmission lines for microwave integrated circuits. The SiO_2-GaAs structures were formed using different techniques, namely, (i) monosilane oxidation in oxygen, (ii) high-temperature tetraethoxysilane decomposition, (iii) high-frequency cathode sputtering of quartz in argon plasma, and (iv) electron-beam evaporation of quartz in a vacuum. The SiO_2 films obtained using monosilane oxidation or electron-beam evaporation of quartz demonstrated better properties. For the Au-Ti-SiO_2-GaAs structures a layer structure transformation was shown to occur, with formation of TiO_x-SiO_2 junction and gold atoms penetration over the whole adhesion layer thickness. The microwave oscillator modules made using the Au-Ti-SiO_2-GaAs (Si) structures demonstrated output power of 10-60 mW in the 8 mm wavelength range.

Keywords: microwave diode, oscillator module, interface between phases, SiO_2–GaAs layer structure, Au–Ti–SiO_2–GaAs multilayer structure.

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1. Introduction

When developing GaAs-based microwave integrated circuits, much consideration is being given to the development of transmission lines based on the metallized SiO_2-GaAs structures. In this case, along with formation of a high-quality metallization to this structure, heavy demands are imposed upon the SiO_2 films and SiO_2-GaAs interface. Among these demands are: high insulating properties; low density of surface states at the SiO_2-GaAs interface; chemical inactivity to GaAs and metallization; high density; low porosity; high adhesion to GaAs; high thermal and radiation tolerance; compositional and surface uniformity of SiO_2 films; manufacturability of the fabrication technique. A considerable experience gained during investigations of SiO_2-GaAs structures intended for various functional purposes evidences that one of the features of these structures is high imperfection of the interface. This imperfection appears during the physicochemical processes used when growing SiO_2 films [1-4].

Choice of techniques to form SiO_2-GaAs structures and exert control over the interface properties seems to be topical because the transmission line characteristics essentially depend on the SiO_2 film quality. That is why our objective was to choose a technique for formation of those SiO_2-GaAs structures that would meet the requirements of microwave engineering, and to study physicochemical properties of the Au-Ti metallization sputtered onto the SiO_2-GaAs structure.

2. Experimental procedure

The epitaxial n-n^+-GaAs structures have been chosen to serve as substrates because it is rather convenient to study such subjects for determination of optimal manufacturing technology for SiO_2-GaAs contacts. Silicon dioxide films were sputtered onto the surface of the above structures using the following four techniques: (i) monosilane oxidation in oxygen at T = 350 °C for t = 15 min.; (ii) high-temperature tetraethoxysilane decomposition at T = 680 °C for t = 150 min.; (iii) high-frequency cathode sputtering of quartz in argon plasma; (iv) electron-beam evaporation of quartz in a vacuum at T = 400 °C. The

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Table 1. Impact parameter Γ (meV) and Hall mobility of charge carriers μ ($cm^2/V \cdot s$) for the GaAs near-surface layer

Si	Type of samples	Parameter	Dose, Gy				
			0	10^3	10^4	10^5	10^6
1	Monosilane oxidation in oxygen (T = 350 °C, t = 15 min.)	Γ μ	23 3600	23 3600	20 4100	20 4000	22 3800
2	Tetraethoxysilane decomposition (T = 680 °C, t = 150 min.)	Γ μ	35 2800	30 3100	25 3400	23 3600	28 3200
3	Cathode sputtering of quartz in argon plasma	Γ μ	33 2900	30 3000	28 3100	29 3000	33 2800
4	Electron-beam evaporation of quartz in vacuum (T = 400 °C)	Γ μ	25 3500	21 3900	20 3900	20 3900	24 3600

SiO_2 films were about 300 nm thick. Au-Ti contact metallization was formed on the SiO_2-GaAs structures that were obtained using the electron-beam evaporation of quartz.

Evidence on chemical composition and structure of the grown SiO_2 layers was obtained using Auger electron spectroscopy (AES) and secondary ion mass spectrometry (SIMS) (argon ions were used for sputtering). The data on the properties of the GaAs near-contact layers were obtained from the photoreflection and photoluminescence spectra.

3. Results and discussion

The AES and SIMS measurements have shown that the film composition was close to that of SiO_2. Etching of SiO_2 film in peroxyammonia showed for every of the four types of samples that GaAs surface was depleted of gallium; the degree of depletion depended on the sample type. To illustrate, the ratio between gallium and arsenic concentrations at the surface after etch removal of films obtained by techniques (i) and (iv) was about 0.4-0.45, while that for the case of technique (iii) was about 0.1. The results of photoluminescence studies also indicate at changes in the structural-impurity composition of the GaAs near-surface layer. The photoluminescence spec-

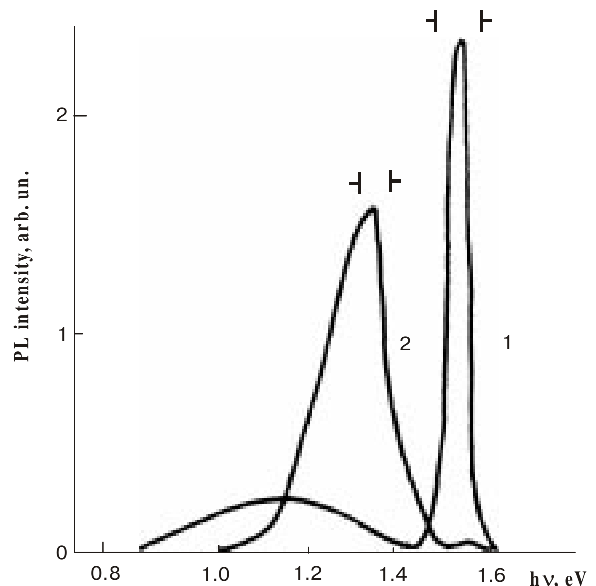


Fig. 1. Photoluminescence spectra (intensity vs photon energy) for GaAs films: 1 – initial n-n^+-GaAs structure; 2 – after removal of a 300 nm thick SiO_2 layer (obtained by monosilane oxidation in oxygen at 350 °C) in the peroxyammonia etchant. The measurements were performed at 77 K.

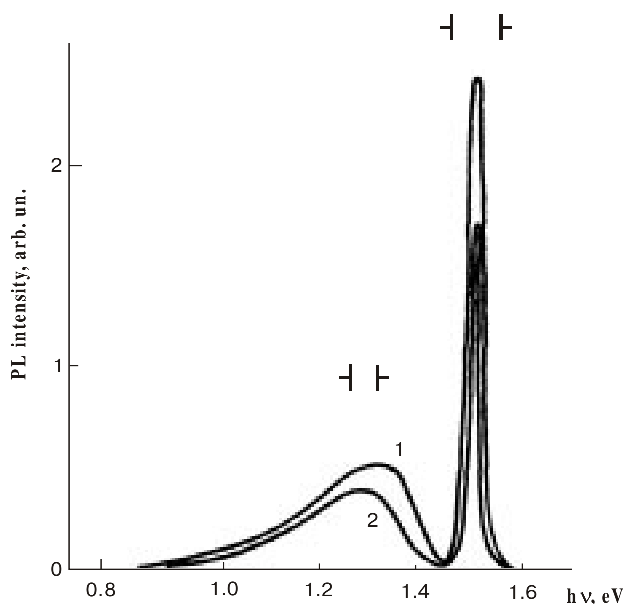


Fig. 2. Photoluminescence spectra (intensity vs photon energy) for GaAs films: 1 – initial n-n$^+$-GaAs structure; 2 – after removal of a 300 nm thick SiO_2 layer (obtained by tetraethoxysilane decomposition at 680 °C) in the peroxyammonia etchant. The measurements were performed at 77 K.

tra taken at T = 77 K on the SiO_2-GaAs structures after removal of the SiO_2 layer obtained by technique (i) show that in this case the properties of the GaAs near-surface layer are close to those of the starting GaAs material (Fig. 1). Along with the principal band, an impurity band is observed in the photoluminescence spectra. This band is related to the $V_{Ga}Te_{As}$ complex [5] (V stands for vacancy, and Te_{As} for a Te atom occupying the As site). In the GaAs near-surface layer of the structures obtained by technique (ii) the intensity of the ~1.33 eV band increased (according to literature, this band is related to the $V_{As}Cu_{Ga}V_{As}$ complex). At the same time, the principal band in these structures was substantially quenched; this fact indicates at intense defect production in the GaAs near-surface layer (Fig. 2).

An analysis of the photoreflection spectra for the SiO_2-GaAs structures prepared using the above techniques showed that the samples obtained using monosilane oxidation (sample 1 in Table 1) and electron-beam evaporation of quartz (sample 4 in Table 1) demonstrated the best structural perfection. The Hall mobility μ of charge carriers in the GaAs near-surface layers of these samples was 1.2÷1.3 times higher than that for the samples 2 and 3. The impact parameter Γ of the photoluminescence spectra broadening may serve as a degree of structural perfection of the near-surface layers. The lower is Γ, the more perfect is the GaAs near-surface layer. One can see from Table 1 that minimal Γ values are demonstrated by the samples 1 and 4. Thus, according to the above results obtained by analytical methods and from the photoluminescence and photoreflection spectra, the best parameters are demonstrated by the SiO_2-GaAs structures obtained using monosilane oxidation in oxygen and electron-beam evaporation of quartz in a vacuum. The SiO_2-GaAs structure obtained with technique (iv) was exposed to Ti metallization followed by gold layer sputtering.

Shown in Fig. 3 are the Auger concentration depth profiles of the components of the Au-Ti-SiO_2 structure

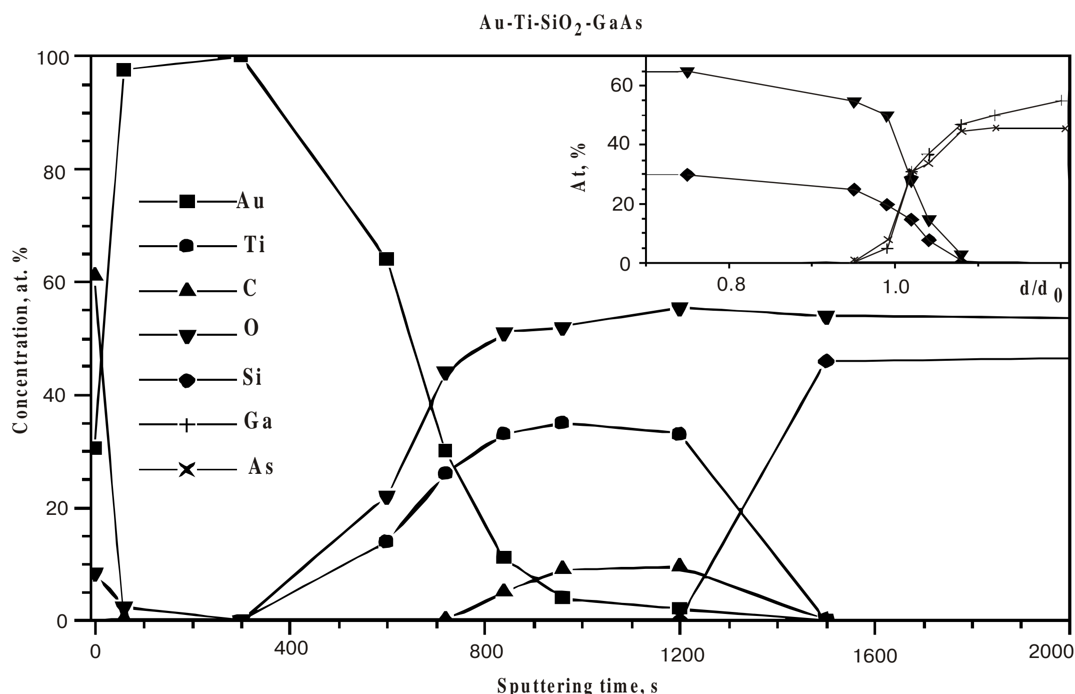


Fig. 3. Auger concentration depth profiles of the Au-Ti-SiO_2 structure components.

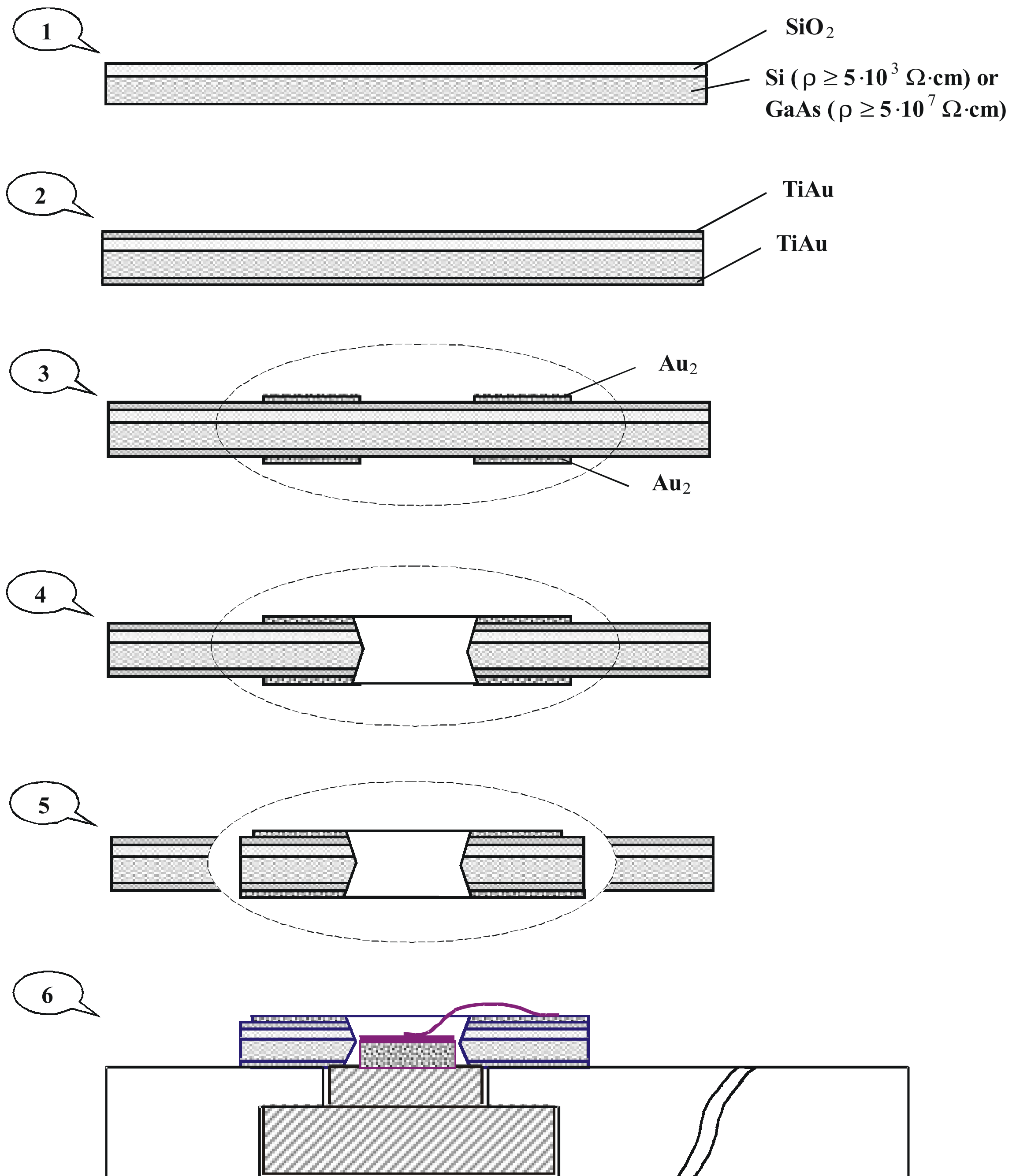
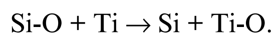


Fig. 4. Technological route for oscillator module manufacturing: 1 - SiO_2 formation on high-resistance Si or semi-insulating GaAs wafers; 2 - sputtering of Ti-Au_1 contact layers; 3 - two-sided photolithography, topology formation; 4 - two-sided photolithography, hole etching; 5 - die separation; 6 - assembling of oscillator module.

formed in the technological mode. Strongly pronounced intermixing effects should be noted. They completely destroy the layered structures of the samples studied. One should expect a substantial spreading of the Ti-SiO_2 interface due to pronounced gettering properties of titanium. But for the chemically passive Au-Ti pair such a deep (over the whole thickness of the Ti film) penetration of gold atoms seems to be quite unexpected.

One may suggest that the reasons for such strong effects of diffusion redistribution of atoms in the contacting layers result from phase changes in the Ti layer. Indeed, it is well known that the Ti-O bonds are intensely formed even at room temperature. So one may assume that during the Ti film deposition and further treatments the Si-O bonds break and new oxides are formed according to the following reaction:



$$\text{Si-O} + \text{Ti} \rightarrow \text{Si} + \text{Ti-O}.$$

That this reaction occurs is also supported by the values of thermochemical parameters of titanium oxide formation. It was stated in [6] that for TiO_2 the heat of formation is –218 kcal/mole, i.e., it is much higher than that for titanium silicides ($TiSi_2$: - 32 kcal/mole; TiSi: - 31 kcal/mole; Ti_3Si_3: -138 kcal/mole). Quick oxygen diffusion into Ti layer leads to the titanium oxide formation. At the same time no titanium silicides are formed (taking into account the sample preparation conditions). Thus at thermal equilibrium the layered heterostructure is transforming with formation of the TiO_x-SiO_2 junction. This process is accompanied by disruption of the titanium-based diffusion barrier that prevented Au diffusion deep inside the heterophase structure. As a result, gold atoms penetrate into the whole adhesion layer.

Similar structure of the Au-Ti-SiO_2 contacts was observed in the Au-Ti-SiO_2-Si samples. Both structures (Au-Ti-SiO_2-GaAs and Au-Ti-SiO_2-Si) were used when producing microwave oscillator modules. The technological route for oscillator module manufacturing is presented in Fig. 4. The high-resistance Si and semi-insulating GaAs wafers 200 + 10 μm thick (resistivity no less than $5{\cdot}10^3$ and $5{\cdot}10^7$ Ω·cm, respectively) served as starting materials. Two-sided photolithography and local chemical deposition of gold were used to form topology. The holes were made using two-sided alignment and chemical-dynamic etching. The IMPATT diode chip was mounted on the heat sink using diffusion welding. The gold lead was welded to mesas and topology elements using thermocompression. The output power of such oscillator modules was from 10 to 60 mW in the 8 mm wavelength range (frequency of 38 GHz).

8. Conclusion

Thus we have developed and realized the technological route for production of oscillator modules (intended to operate in the millimeter wavelength range) using high-resistance Si (GaAs) substrates coated with SiO_2-Ti-Au layers.

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