Specific features of the formation of optical waveguides, contact pads and electrical interconnections on lithium tantalate substrates

I V Konyaev¹, I I Borodkin¹ and E N Bormontov²

¹JSC «Scientific Research Institute of Electronic», 394033 Voronezh, Russia
²Voronezh State University (VSU), 394036 Voronezh, Russia

E-mail: www.450_asd@mail.ru

Abstract. The article considers the formation of titanium channel optical waveguides in LiTaO₃ substrates. These structures were obtained by dry etching of grooves in SF₅ plasma and magnetron sputtering of titanium film. After that, waveguides were formed by plasma etching using photoresist as mask. Technological features and modes of microstructure production are described. Al contact pads were produced by magnetron sputtering thin metal films on LiTaO₃. Aluminum wires were ultrasonically bonded to Al contact pads using Delvotec 5630. The developed technology of formation of contact pads and bonding modes made it possible to obtain a bonded joint with a bond strength of 23-25 Gs.

1. Introduction

Nowadays, monocrystalline LiTaO₃ substrates are widely used in the manufacture of such functional electronics as filters on surface and bulk acoustic waves (SAW/BAW), high-density storage devices, optical waveguides, electric field sensors. The scientific principles upon which these kinds of devices are based are the interaction of volume and surface waves in solids with an electromagnetic field [1, 2]. A method of making microstructures on lithium tantalate substrates requires special surface treatment for creating relief.

For a long time, the main method of surface preparation was liquid etching in acid solutions. However, the method of liquid etching does not allow obtaining required selectivity, profile anisotropy, and the process is more environmentally harmful. As the technology develops, dry etching methods are more widely available. An increase in the role of plasma etching processes is related to the need to obtain high-resolution topological elements. An important advantage of dry etching is its selectivity, which creates the opportunity for wider choice of etching mask. Reactive ion etching of lithium tantalate using CF₄/Ar, CF₄/H₂, CF₄/Ar/H₂ gas mixture were studied by T. Fujii and S. Yoshikado [3]. The highest etch rate and the best anisotropy were obtained with the CF₄/Ar gas mixture. However, the etch rate was no more than 10 nm/min. Kinetics of plasma etching process is also presented in [4-5]. More flexible control capabilities of parameters of technological process are complicated by the multifactorial influence and the complex nature of functional dependencies.

Traditional technology in channel waveguides making, which has proven itself well for LiNbO₃, is based on the diffusion of pre-deposited metal. However, lithium niobate has less resistant to radiation, since exposure to light in the visible range leads to the appearance of defects in it. LiTaO₃ is significantly
more durable. It has the damage threshold about two orders of magnitude higher in radiation energy density. At the same time, the diffusion of metals in lithium tantalate is ineffective or imposes additional difficulties due to the low Curie temperature (610 °C). It is required additional polarization of the samples at high-temperature diffusion (T= 950±1100° C) [6]. An alternative way to form the topological pattern is preliminary etching of the desired geometry grooves, followed by metal deposition. The main advantages of channel waveguides are low losses due to the possibility of more efficient matching of the refractive indices of the waveguide and the substrate.

BAW filters are also made by technology of preliminary etching profile in the substrate. These structures do not always have an optimal electromechanical coupling factor and reflection coefficient. Active researches of various options for the technology of applying interdigital transducers (IDTs) are carried out. These technologies are based on different metallization systems located in the plane or volume of the substrate [7]. Two-layer metallization is widely used in electrode manufacturing of SAW/BAW filters on LiTaO₃ substrates [8]. The bottom layer was formed by copper deposition into pre-etched grooves. Then the top layer of aluminum was sputtered. This structure has a good electromechanical coupling factor, reflection coefficient and high Q factor, which makes it possible to create high-sensitivity devices.

Thus, one of the main design decisions in making of electrode decoupling, optical waveguides, resonators and reflectors are the etched profile in the substrate and a good adhesion of deposited metal films. These are important conditions for wire bonding between contact pads.

2. Equipment and materials
Plasma-chemical etching of lithium tantalate was carried out on a Corial D250. This unit is equipped with a planar diode system of electrodes. The gas supply system allows achieving uniform volumetric mixing in the reaction-discharge chamber. The etching rate was determined by the gravimetric method using a high-precision analytical balance Vibra HTR-220CE. Aluminum and titanium thin films were evaporated by magnetron sputtering system Oratorio-5 at high-vacuum pressure. Microposit S1813 G2 SP15 photosist with thickness of 1 μm was coated by spin coating method at 4000 rmp. Lithographically patterned Al film was etched in (NH₄)₂S₂O₈ : CH₃COOH : H₃PO₄ : H₂O = 7:4:14:15 solution. Post oxygen plasma clean was done to remove the photosist film using an SNT P 200 tool. FN-115 negative photosist was used as a mask for Ti dry etching. An annealing process was performed in an inert nitrogen atmosphere at 400 °C on single-zone multi-pipe diffusion system. Ultrasonic wire bonding of Al wire was carried out onto aluminum contact pads using a semi-automatic wedge bonder 5630. Surface roughness evaluation was conducted using the optical microscope Jenatech and scanning electron microscope JEOL JSM–6610A.

3. Results and discussion
Dielectric-metal contact plays a significant role in operation of optical waveguides. Lithium tantalate substrates were preliminarily etched in an oxygen low power plasma for 2 min to remove organic compounds adsorbed from the atmosphere. This has made it possible to have better adhesive properties.

As noted above, grooved electrodes allow to form channel optical waveguides in the bulk of the LiTaO₃ substrate and improve the characteristics of devices. The thickness of metal, the etch depth and etched profile on the surface are determined by the circuit design of a particular device and, first of all, depend on the frequency range of device.

The scheme of fabrication of channel optical waveguide on LiTaO₃ substrate is shown in figure 1. Firstly, layer of Al 500 μm thick was deposited by magnetron sputtering at 0.5 Pa pressure using Oratorio-5 setup. Then wafer was covered by positive photosist with 1 μm thickness using spin-coater. Further, the photosist layer was soft baked, exposed and developed the photosist mask. Wet etching of aluminum was carried out in open spaces. At the next stage, the remaining photosist mask was removed in the O₂ plasma. The grooves in lithium tantalate substrate were etched by plasma chemical etching in SF₆ on Corial D250. Plasma chemical etching of LiTaO₃ with fluorine radicals leads to the formation of a non-volatile sediment. It has already been reported that the sediment accumulated on the
sample was LiF. Lithium fluoride has a boiling point of 1676 °C and a melting point of 842 °C [9]. The surface temperature of LiTaO₃ during etching does not reach this boiling point. Moreover, it cannot be removed by ion sputtering due to low ion energies. For further movement along the technological process route, lithium fluoride and Al mask were removed in peroxide-ammonia mixture and orthophosphoric acid, respectively, followed by washing in deionized water. Titanium layer was sputtered on a clean surface in an inert Ar atmosphere at a pressure of 0.5 Pa. In order to create metal-filled grooves, it is necessary to repeat photolithography using negative photoresist. FN-11S photoresist was coated on substrate, and then the photoresist mask was developed. After that, Ti was dry etched. Finally, the photoresist mask was removed and substrate was cleaned by isopropanol and deionized water.

![Figure 1. The scheme of fabrication of channel optical waveguides on LiTaO₃ substrate.](image)

Surface morphology of the sample was investigated by scanning electron microscopy (SEM). Figure 2 shows SEM images of Ti waveguides on LiTaO₃. It should be noted that the resulting structure is almost planar (see figure 2a). Based on magnetron sputtering deposition technology, titanium films has a good adhesion lithium tantalate substrate. There are no cracks and delamination. The chemical dry etching of Ti through a negative photoresist mask is characterized by a small groove at the edges of the elements. The quality of the edges of the elements depends on alignment accuracy of the layer of photoresist mask and etched elements on LiTaO₃. Figure 2 (b) shows that the isotropy of the etching process lead to the wavy edges of the etched structures.

![Figure 2. SEM images of Ti waveguides on LiTaO₃: a) angle view b) top view.](image)
Contact pads (CP) or bond pads (BP) are important components of functional devices of microelectronics and microsystem technology. Conventional materials used in production of contact pads and electrical connection are Al, Au and Cu. This paper presents the results of formation of aluminum pads and its connection. A thin-film deposition technique used for fabrication Al contact pads. The process consists of the following steps: magnetron sputtering of metal, conventional lithography and wet etching. Adhesion to the surface of lithium tantalate is a significant parameter of sputter deposition of metallic films.

Magnetron sputtering was carried out in two stages. At the first stage, a seed layer of 20 nm was deposited on LiTaO$_3$ at the temperature of 100 °C. The thickness was built up to 0.3 μm at a higher rate, followed by annealing in nitrogen atmosphere at T = 400 °C. According to [10], makes it possible to improve adhesion to the substrate. CPs of various sizes were developed using a photomask. Bonding technology has a major impact on the failure modes of devices. Breakage and adhesion strength of the connections were performed after bonding contact pads.

The connections between contact pads were formed by wire bonding. Aluminum CPs of sizes 100 × 100 μm, 150 × 90 μm, and 60 × 60 μm is shown in figure 3. Scheme of wire bonding included the connection of CPs of various sizes. A 50-μm diameter Al wire was ultrasonically bonded to CPs.

![Figure 3. SEM images of Al contact pads: a) size 100×100 μm at 200x; b) size 150×90 μm at 600x.](image)

The aluminum-aluminum wire bond system is extremely reliable because it is not prone to intermetallic formation and corrosion. Aluminum wire on aluminum metallization welds best ultrasonically [11]. The weld is produced by the application of high frequency vibratory energy as the parts are held together with force. The rubbing action that occurs at the metallic interface displaces metallic oxides, foreign materials, to expose fresh clean metallic surfaces for bonding [12]. A serious problem in the manufacture of microelectronic devices is the surface quality of the contact pads. Surface contamination and the structure of aluminum film have a significant influence on the adhesion of connecting wire and its reliability. Adsorbed fluorine atoms, organic impurities and aluminum oxidation exert the great influence. Contaminants such as oxides and organic residues impair the bondability to a considerable extent and are very resistant to conventional wet cleaning methods [13]. Al CPs were exposed to clean surface in Ar/SF$_6$ plasma for 30 sec. Ar plasma is used to activate Al surface by physically bombarding it with Ar ions or atoms. SF$_6$ plasma is used to clean surfaces because it can eliminate organic contaminants by chemical reaction.

Ultrasonic wire bonding was carried out on aluminum surface by wedge-wedge method. We use 50-μm diameter Al wire. Three distinct settings: power, time, and force were varied to find and propose the optimal process parameters for strong mechanical and electrical bond between Al wire and Al surface of CPs. The following bond parameters were employed at frequency of 60 kHz: power - 90 machine units, bond force – 0,59 N (60 gram force) and bond time - 40 ms. Figure 4 shows wire-bond loop
formation for wedge bonding. In addition, there are marks of test research of wire bonding in other modes, which did not allow achieving a stable connection.

An analysis of the pull-out strength of loops showed a good results. Strength was determined by tensioning the wire until it breaks how it described in [14]. The resulting value of the breaking load was 23-25 gf (0.23-0.25 N). Analysis of the wire break point shows its localization at bond (neck break when wedge bonding). A good bond connection of the wire to LiTaO₃ substrate is provided.

**Figure 4.** SEM images of bonded Al contact pads by Al wire d=50 μm.

### 4. Conclusion

Preliminary treatment of lithium tantalite substrates in oxygen plasma has improved interface adhesion strength of Ti-LiTaO₃. The topology of optical waveguides and contact pads was annealed in nitrogen atmosphere at T = 400 °C to increase the adhesion force. Plasma etching technology was applied to develop of titanium channel optical waveguides on lithium tantalate substrates. Ultrasonic wedge-wedge bonding was used to connect Al contact pads. The pull-out test of loops was performed to measure of breaking load. Successful results of the quality of a bonded joints and the reproducibility of technology were obtained.

**Acknowledgements**

This paper is supported by Scientific Research Institute of Electronic.

**References**

[1] Hashimoto K, Yamaguchi M, Mineyoshi S, Kawachi O, Ueda M and Endoh G 1997 *Proc. IEEE Ultrason. Symp.* 1 245-54
[2] McCann D F, McGann J M, Parks J M, Frankel D J, da Cunha M P and Vetelino J F 2009 *IEEE Trans Ultrason Ferroelectr Freq Control.* 56(4) 779-87
[3] Fuji T and Yoshikado S 2004 *Electrical Engineering in Japan* 149(2) 18-24
[4] Plehnert C, Norkus V, Möhling S and Hayes A 1995 *Surf. Coat. Technol.* 74/75(2) 932-36
[5] Kamimura R and Furuta K 2017 *IEICE Trans Electron* E100.C(2) 150–55
[6] Atuchin V V, Ziling K K and Shipilova D P 1984 *Quantum electronics* 11(5) 994–98
[7] Kadota M and Kimura T 2006 *Jpn. J. Appl. Phys.* 45(5S) 4647-50
[8] Kimura T, Kadota M and Ida Y 2010 *IEEE MTT-S International Microwave Symposium* 1740–43
[9] Tamura M and Yoshikado S 2001 *Sci. Technol. Adv. Mater* 2(3-4) 563-69
[10] Fu X, Zhang G, Zhang J, Guo K and Pan Y 2018 *Coatings* 8(5) 186
[11] Murthy K S R C 2015 *IAERS* 2(9) 1-7
[12] Maeda M, Kitamori S and Takahashi Y 2013 *Science and Technology of Welding and Joining* 18(2) 103-7
[13] Chong Y F, Gopalakrishnan R, Tsang C F, Sarkar G, Lim S and Tatti S 2000 Microelectronics Reliability 40(7) 1199-206
[14] Wang C and Sun R 2009 Modern Applied Science 3(12) 50-6