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Interface Reactions in $LiNbO_3$ Based Optoelectronics Devices

Hirotoshi Nagata, Yasuyuki Miyama, Kaoru Higuma, Yoshihiro Hashimoto,
Futoshi Yamamoto, Yuuji Yamane, and Miki Yatsuki
Optoeiectronics Research Division.
New Technology Research Laboratories.
Sumitomo Osaka Cement Co., Ltd.
585 Toyotomi-cho. Funabashi-shi, Chiba 274-9601. Japan

ABSTRACT

We present secondaly ion mass spectrometry (SIMS) study results on interfaces of $LiNbO_3$ based optoeleclronic devices, which have been performed in order to examine the cause of device failures. The devices are widely used in current high-speed optica1 fiber communication systems. and such investigation from a materials-viewpoint is' important to improve the device quality. Especially. the device long-term stability is strongly affected by alkali-contaminants diffused into the SiO_2 buffer layer of device, and here we confirmed that an adoption of common Si_3N_4 passivation is effective in preventing the process-induced contamination without any influence to device performance.

INTRODUCTION

Since $LiNbO_3$ based optical waveguide modulators are widely used in global fiber communication systems, their long-term reriability has been carefully investigated from the view point of stability of device performance. such as do drift phenomena. The latest Telcordia GR-468-CORE standard comments' on relisbility and quality requirements for $LiNbO_3$ modulators in addition to conventional laser devices [1]. However, to our knowledge, reports on problems in devicc quality due to thc $LiNbO_3$ modulator fabrication processess are limited. although a demand for $LiNbO_3$ modulators is rapidly increasing. For instance, the magnitude of the dc drift in modulator optical output is largely enhanced by alkali-contaminants injected into a SiO_2 buffer layer covering the $LiNbO_3$ substrate [2]. Because the dc drift is a main cause of device wear-out failures, the drift must be suppressed [3]. We found previously that the alkali-contamination was caused by wet-processses for exposed SiO_2 layer, such as photolithography. wet-etching, etc. In this report. applicability of a Si_3N_4 passivation layer, common material in Si device processes. to $LiNbO_3$ modulators is shown. Thc Si_3N_4 layer works not only as the passivation layer but also as the giue layer, for Au/Ti electrodes formed on modulator surface.

STRUCTURE OF $LiNbO_3$ MODULATORS

Figure 1 shows a schematic cross-section of the $LiNbO_3$ optical intensity modulators. mainly consisting of an $LiNbO_3$ substrate with the buried optical waveguides, the SiO_2 buffer layer covering the $LiNbO_3$ surface, and the thick gold electrodes. The optlcal waveguides were formed by a thermal diffusion of metallic Ti lines at approx. 1000˚C. After the waveguide formation, thc SiO_2 layer was deposited by a vacuum evaporation method and annealed at 600˚C in an oxygen atmosphere. On the SiO_2 surface. the Au/Ti binary film was deposited by a sequential vacuum evaporation of Ti and Au, as a glue layer for the thick Au electrodes prepared by all electro-plating method. The role of the Ti layer is to increase the bonding strength of Au layer to the SiO_2. The Au electrodes were grown between photoresist walls. Which had been patterned on the Au/Ti binary layer. and these photeresists were chemically removed. In the last process, the Au/Ti binary layer left between the Au electrodes was chemically etched to expose the SiO_2 surface as shown in Fig. 1

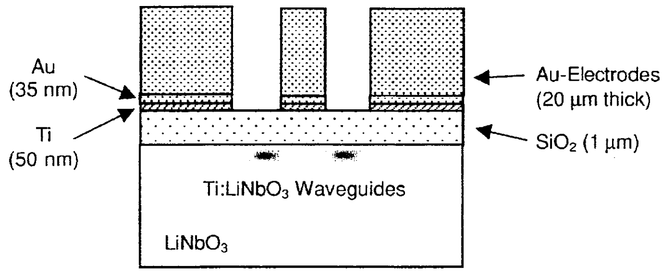

Fig. 1 *Cross-sectional illstlation of $LiNbO_3$ optical intensity modulator.*

In the above mentioned fabrication process of $LiNbO_3$ devices, some chemicals for wet-processes may contaminate the device constituent materials, especially a $LiNbO_3$ wafer surface and a SiO_2 buffer layer. For instance, an inorganic-based photoresist-developer, including sodium silicates, diffuscs alkali-contaminants into the SiO_2 buffer layer as shown in SIMS analysis results of Fig. 2. In this sample, the SiO_2 layer was found to be contaminated by Na and K, although thin Au/Ti layers covered the layer. The Li detected through SiO_2 layer is considered to come from the $LiNbO_3$ substrate. Figure 3 shows another example of thc SiO_2 layer contamination due to chemical treatment of thc wafer. Before the electrodes plating process, the Au/Ti surface is slightly etched using commercial chemicals in order to increase the bonding strength of electro-deposited Au layer. With the chemicals containing fluorides, F-residue was found in the Au/Ti layer. Further, the F ions seemed to diffuse into the SiO_2 layers

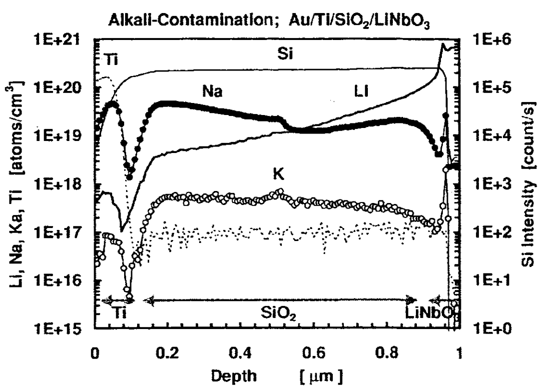

Fig. 2 *SIMS results on SiO_2 layer of'defective modulator.*

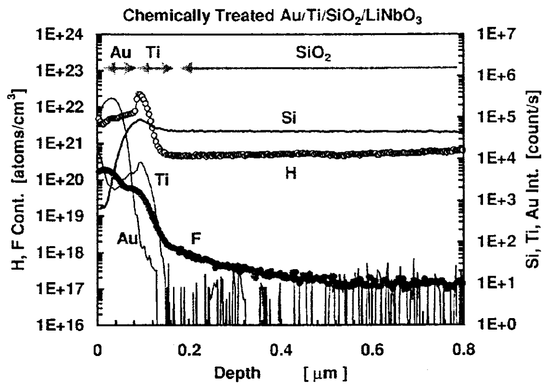

Fig. 3 *SIMS restlts on chemical1y etched Au/Ti/SiO_2 surface.*

SILICON NITRIDE PASSIVATION

Because the contaminated SiO_2 buffer layer deteriorates modulator performance and shortens a devicc lifetime, the deposition of silicon nitride passivation layer on the SiO_2 is thought to be effective. The 100-150 nm thick silicon nitride film was synthesized by reactive RF-sputtering of the pure Si target with an Ar/N_2 mixture. The substrate was not intentional1y heated during the sputtering deposition. The obtained film was confirmed to be in Si_3N_4 composition by an X-ray photoelectron spectrometer. On the Si_3N_4-passivated SiO_2 layer, the patterned Au-electrodes were prepared by an electro-plating method after a deposition of the thin Au/Ti binary layer on the Si_3N_4 passivation film. The Au/Ti layer left between a pair of electrodes was chemically removed and the Si_3N_4 film exposed.

The x-cut $LiNbO_3$ modulator samples with Si_3N_4 passivation were designed to work in 10 Gb/s optical transmission systems, and here we examined whether the silicon nitride passivated modulators could perform expected E/O characteristics or not. Table 1 is a list of E/O parameters measured on four modulators from three different wafers (wafer #101 , #102, #103). The first line of Table 1 denotes our expected specifications for this modulator design. If an electrical conducting layer exists between the electrodes. there is a possibility of an increase in $V\pi$ and dc drift performnances. However, concerning E/O parameters, we conclude that the silicon nitride passivated x-cut $LiNbO_3$ modulators can exhibit the performances meeting 10 Gb/s systems without any significant problems.

Table 1 Electro-Optic performances of x-cut $LiNbO_3$ modulators with Si_3N_4 passivation.

Sample No.	N_2 Flow Rate [sccm]	Intensity Modulator DC $V\pi$ @ 1 kHz [V]	AC $V\pi$ @ 5.33 GHz [V]	Electrode B.W. [GHz]	Phase Modulator AC $V\pi$ @ 10.66 GHz [V]	Electrode B.W. [GHz]	On/Off Extinction Ratio [dB]
Design	-	≤ 5	≤ 6.5	-	≤ 10.5	-	≥ 20
#101-1	4.1	5.0	6.5	5.7	9.8	5.7	24.0
#101-3	4.1	4.9	5.5	6.2	9.2	5.5	34.1
#102-4	4.1	4.8	6.3	5.5	9.2	4.9	27.4
#103-6	4.1	4.8	6.1	5.3	9.6	5.3	21.5

Figuie 4 exhibits the dc drift measurement results on x-cut $LiNbO_3$ modulators, with the Si_3N_4 passivation layer (solid curve) and without any passivation (dashed curve). The measurement was carried out at 85 ˚C in order to accelerate the dc drift phenomenon. The vertical axis denotes the dc bias voltage that is applied to adjust the state of optictd output signal. If the bias voltage drifts fast. as the dushed curve, driver-circuits get to no longer controll the modulator (failure). The cause of such defective drift perfomance was found to be alkali-contamination of the SiO_2 buffer layer as shown in Fig. 5 (SIMS results of failed modulator surface) [2-4]. The alkalli-contaminants were considered to diffuse into the exposed SiO_2 layer during wet processing of wafers. On the other hand, when the Si_3N_4 passivation layer was inserted between SiO_2 and electrodes, the diffusion of alkali-contaminants was suppressed as shown in Fig. 6.

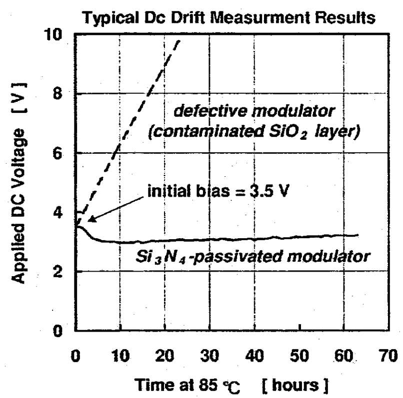

Fig. 4 *Example of'dc drift performance of modulators.*

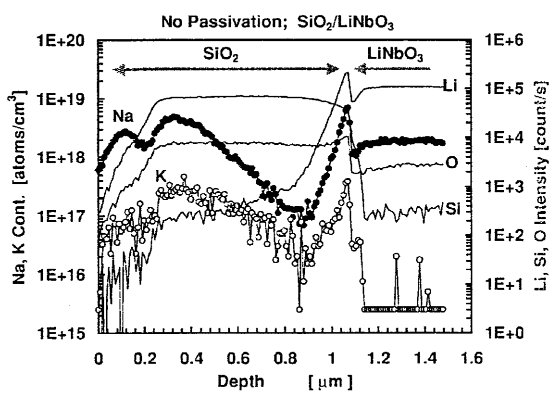

Fig. 5 *SIMS results of' the failed modulator without Si_3N_4 Passivation.*

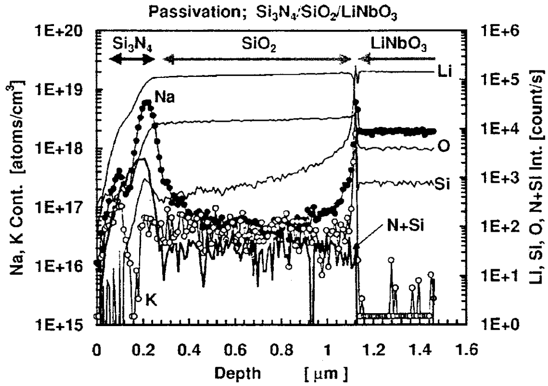

Fig. 6 *SIMS results on modulator surface Passivated by Si_3N_4 thin layer.*

In addition to the passivation effect, the insertion of Si_3N_4 layer was found to Improve bonding strength of the electrode layer. In order to increase the bonding strength of Au-electrodes to SiO_2. buffer layer, a thin Ti film is usually inserted in-between. However, when the Ti layer is excessively oxidized due to a fluctuation of SiO_2 processes and/or H_2O contaminants in the SiO_2 layer, the bonding strength of the electrode is largely decreased [5]. Such defective electrodes were found to peel-off easily at the boundary between SiO_2 and Tl. The Si_3N_4 layer inserted between SiO_2 and Ti layers was expected to strongly prevent the excess oxidization of the Ti, bonding the electrode layer. Here in order to check the electrode bonding performance qualitatively, the electrodes of silicon nitride passivated wafers were intentionarlly peeled-off, and a debonding of the $SiO_2/LiNbO_3$ boundary was observed (not at the Ti/Si_3N_4 interface). The result suggests that use of the silicon nitride passivation film in $LiNbO_3$ modulators is advantageous also in the mechanical performance.

Li-DIFFUSION INTO SiO_2 LAYER FROm $LiNbO_3$ SUBSTRATE

In fabrication processes of $LiNbO_3$ modulators. a diffusion of Li^+ ions into the SiO_2 buffer layer from the substrate itself seems to be an inevitable problem as shown in the above SIMS results. Fortunately, we have not found any significant deteriolation in modulator performance possibly due to the Li-diffusion. However, an investigntion on Li-diffusion is necessary to improve the modulator quality and process repeatability.

Figure 7 reveals SIMS results on A1-thin-film polarizer installed directly on x-cut Ti:$LiNbO_3$ waveguides, which can cut selectively the TM-mode light. In order to achieve higher polarization extinction ratio and chemical stability of the A1 layer [6]. we designed the polarizer to have a layer-structure of "SiO_{2-x}/Ai/SiO_{2-x}//$LiNbO_3$-substrate". The thicknese of the SiO_2 inserted between Al (and $LiNbO_3$ must be 10 nm to obtain the most effective interaction of light between waveguide and AI layer. All films were prepared by a multi-target RF-sputtering technique in the same deposition chamber. A notable fact found in Fig. 7 is that the Li ions diffuse through the metallic Al layer toward the thick SiO_{2-x} layer. A higher affinity of Li to SiO_2[7] may be a cause of the phenomenon. Although the fabricated polarizers are working without failures, because there is a possibility that condengation of alkali-ions at the interface deteriorates the bonding strength, further investigation on the phenomena from a long-term viewpoint is needed.

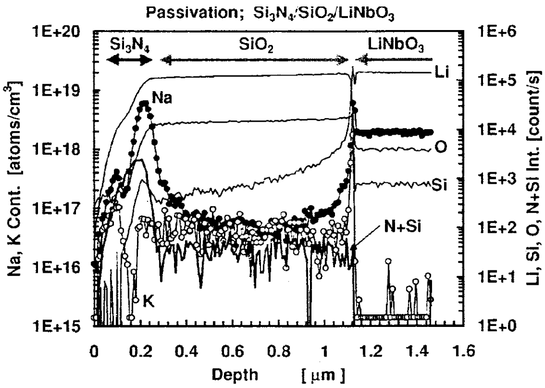

Fig. 7 *SIMS results On Al-thin-film polarizer.*

CONCLUSION

Typical SIMS measurement results on $LiNbO_3$ optical modulator devices were presented. The process originated alkali-contaminants in the SiO_2 buffer layer deteriorated device performances, and was confirmed to be able to be suppressed by the insertion of a Si_3N_4 passivation layer between SiO_2 and surface-electrode layer. The diffusion of Li^+ ions from $LiNbO_3$ itself into the SiO_2 film was also found, although its effect to device performances and mechanical reliability is not known at this time.

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