Process control for a SiO_2 buffer layer of $LiNbO_3$ modulators to obtain reduced dc drift performance

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1 Introduction

The dc drift phenomena are an inevitable problem for $LiNbO_3$ (LN) modulators, depending on the electrical characteristics of device constituent materials.[1,2] One effort has been devoted to excluding the necessity of the dc bias application itself (dc bias free) by a chip-by-chip tuning of the optical output modulation state [3,4] but other efforts to achieve repeatable fabrication of modulators with the same drift magnitude are needed. Especially for broader band LN modulators, the increased thicknesses of the SiO_2 buffer layer and the Au electrode pattem tend to enlarge the magnitude of the temperature-dependent drift phenomenon, [5] making it difficult to realize dc-bias-free modulators. The purpose of this communication is to clarify the fabrication process parameters important to reducing the dc drift and to repeatedly producing LN modulators with a smaller dc drift.

The initial stage of the dc drift, the short-term dc drift in other words, was previously reported to be affected by the characteristics of the SiO_2 buffer layer, which depend[1,6] on the SiO_2 deposition method. However, in volume production of LN modulators, the SiO_2 characteristics were found to have a wide fluctuation, even though the same deposition conditions were adopted, especially in a vacuum evaporation deposition, leading sometimes to an increase in the rejection of devices due to large dc drift. As a result of investigations of such undesirable fluctuations in the buffer layer fabrication process, here we propose the use of the refractive index of the buffer layer as a critical limit value for process control.

2 Screening of Buffer Layer by the Refractive Index

Figure 1 shows the ordinary (solid curves) and extraordinary (dotted curves) dc drift behavior of Z-cut LN Mach Zehnder (MZ) modulators similarly fabricated, but in different fabrication batches. The modulators consisted of 0.8-µm-thick SiO_2 buffer layers, thin Si layers, and coplanar Au electrode patterns. The buffer layer was formed by conventional vacuum evaporation deposition of the silicon oxide material followed by an annealing process at 600∞C in the oxidizing atmosphere to eliminate oxygen defects in the layer. [1] In the measurements, the modulator was kept at 80∞C and biased initially at dc=3.5 V, and then the applied dc bias voltage was adjusted to maintain the optical output modulation (λ1.5 ≃ µm) at the initial state. The extraordinarily large drift voltage, the dotted curves in the figure, was considered to be due to an anomaly in the buffer layer for the following reasons. Similarly large dnfts were observed in other modulators, in which the buffer layers were deposited in the same and neighboring process batches, independent of the difference in the LN wafer lot. Further, the magnitude of the initial drift stage has already been found to be affected by the buffer layer rather than the LN wafer, and the present extraordinary drift was similar to that of modulators with sputtering deposited SiO_2 layers. [6-8]

As a possible reason for this buffer layer anomaly, deterioration in the chemical purity of the material was suspected at first, because of the existence of contaminant ions in the SiO_2, which might increase the electrical conductance and the dc drift, for instance. In this regard, the buffer layers of the inferior modulators were inspected by electron probe microanalysis (EPMA), but no particular contaminations were found. Further, the purity of the source material for the vacuum evaporation deposition process was measured by chemical analyses to be almost identical both before and after the deposition process.

Another possible cause of the buffer layer fluctuation was considered to be physical structure, such as film density. Here we used the refractive index measured for the annealed buffer layer by a prism coupler (λ=633 nm) as an index for the density. Because the buffer layer had been sufficiently oxidized by the wet O_2 annealing, the measured refractive index was thought to indicate mainly a difference in the film density, and the effect of H_2O (-OH) absorbed into the film. Figure 2 shows the refractive index data for the annealed buffer layers that were deposited on different dates using the same deposition equipment. Although the

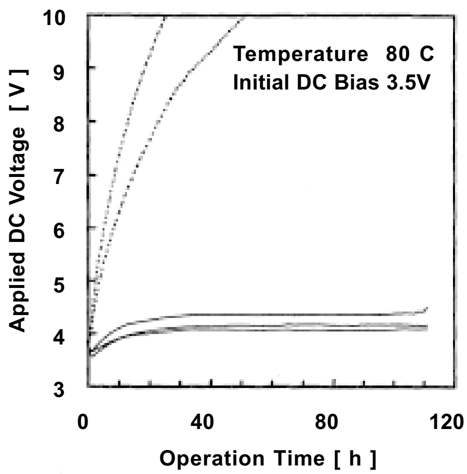

Fig. 1 The dc drift in the applied dc bias voltages of LN modulators fabricated in different process batches, measured at 80°C with an initially applied dc bias of 3.5 V.

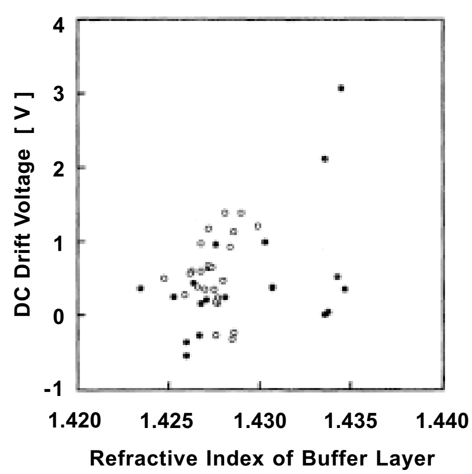

Fig. 3 Relationship between the refractive index of the buffer layer and the dc drift voltage. The drift voltage was measured after 100 h of device operation at 80°C. The black and white marks denote the differences in the buffer layer thickness.

deposition conditions were set to be the same for each of the deposition batches, complete control was difficult for parameters such as the amount of SiO_2 source material, the deposition rate, etc. As seen, after the 1996/9/22 plot, the measured refractive index increased unexpectedly to about 1.44 and was largely scattered. Further, the buffer layers of modulators showing an extraordinary large dc drift, like the dotted curves in Fig. 1 , were traced to be the films deposited during this process period. On the other hand, all the other modulators that were produced before the 1996/9/22 batch showed ordinary drift behavior, as shown by the solid curves in Fig. 1.

Figure 3 shows the relation between the dc drift voltage after 100 h of operation at 80°C and the refractive index of the buffer layer in the corresponding modulators. The dc drift voltage denoted the subtraction of the initial dc=3.5 V bias from the dc voltage applied at 100 h in Fig.1. Data for the extraordinary modulators are not plotted in Fig. 3 because they drifted rapidly over the limit voltage (10 V) of the measuring system within several tens of hours. The black and white marks in the figure correspond to modulators with the 1.0- and 1.1-μm-thick buffer layers, respectively. Although the magnitude of the measured drift was within the allowable range for commercial modulators.[2,9] a weak correlation was found between the drift voltage and the refractive index. A tendency was observed for buffer layers with higher refractive indices to lead to larger dc drift. This result was consistent with the process fluctuation found in Fig. 2 and with the previous result that modulators having a sputtering deposited buffer layer (refractive index ≥ 1.460) showed significantly large dc drift.[6.7]

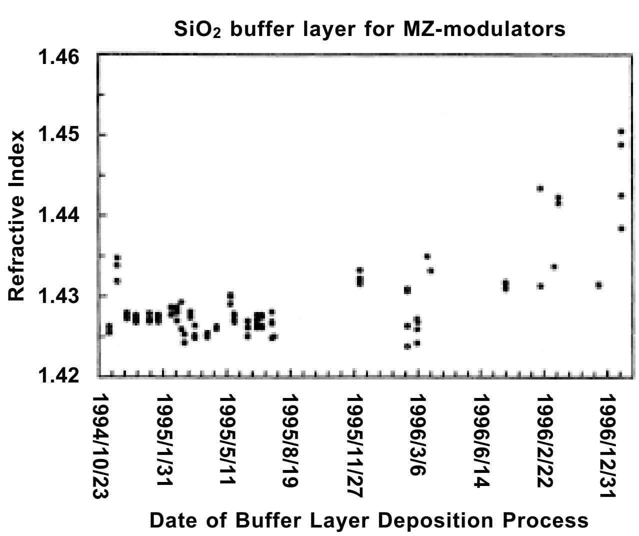

Fig. 2 Refractive index values measured for annealed SiO_2 buffer layers that were prepared on the different dates (batches) by the vacuum evaporation deposition process.

These results indicate that the measurement of the refractive index for the buffer layer was useful to screen the processed LN wafers with regard to dc drift failure. In the case of Figs. 2 and 3, the averaged refractive index and the upper (UCL) and lower (LCL) critical limits using a 3σ control were derived to be 1.42790, 1.43397, and 1.42183, respectively. Such critical values are now being investigated further, including a larger volume of data, for use as practical threshold values for in-process screening tests.

3 Control of Buffer Layer Refractive Index

The refractive index of the buffer layer varies, depending complicatedly on the film deposition conditions. such as the deposition rate, substrate temperature, gas pressure, etc. For instance, Fig. 4 shows the relation between the refractive index and the corresponding deposition rate for the buffer layer fabrication processes of Fig. 2. The observed tendency is consistent with results reported for vacuum evaporation depositions of other oxide films; i.e., larger grains growing in the films when the deposition rate was faster, which leads to a higher film density and also a higher refractive index.[10] Furthermore, the results suggest that the buffer layer deposition rate was also used as an important process parameter for reduced dc drift modulators.

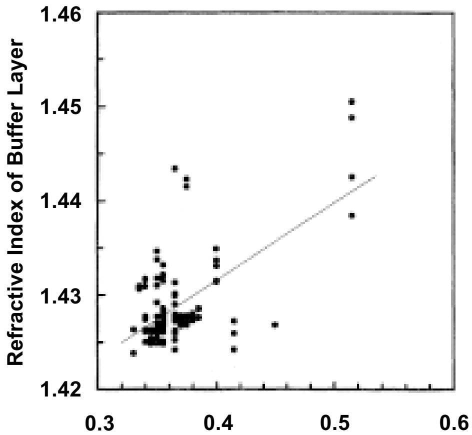

Fig. 4 Relation between the refractive index and the deposition rate for a SiO_2 buffer layer.

4 Conclusion

The correlation between the refractive index of the SiO_2 buffer layer and the magnitude of the dc drift was experimentaily confirmed for LN MZ optical intensity modulators. Although the reason for this observed correlation requires further investigation, the result can be usefully applied to the control of the buffer layer formation process and its screening. Buffer layers with lower refractive indices, 1.42 to 1.43 here, seemed to be suitable to reduce the dc drift phenomenon of the modulators. Currently, however, the scattering of data used here was so great that it was difficult to determine the screening criteria at a specific index value. Further investigation is now proceeding in our fabrication process.

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