Applied-voltage induced fatigue of lithium niobate waveguide

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z-cut lithium niobate optical modulator devices were ac ($V_{p\text{-}p}$ = 20 V) operated at 130°C with an accumulated dc bias voltage of 4 and 8 V. A consequent dc drift phenomenon was larger for the 8 V bias application. After the operation, inversed domains were found along the Mach-Zechnder waveguides, particularly on the waveguide placed under the hot electrode. The results suggested that the device operation at higher voltage and temperature led to an accelerated dc drift and a fatigue like deterioration of the lithium niobate material. © *1996 American Institute of Physics.* [S0003-6951(96)03403-7]

A high speed optical modulator made of *z*-cut lithium niobate substrate has been evaluated for use in optical communication systems. The dc drift phenomenon of the optical output should be small and predictable in order to assure a reliable long-term operation of the device. In this regard, some equations to estimate the drift were proposed in which a dielectric relaxation in device materials was considered.[1-4] There, only the device operation temperature was regarded as an acceleration factor of the drift phenomenon, and the activation energy of the dc drift was reported to be 1 eV from several researchers.[5,6] Because the dc drift suppressed the actually applied dc bias was accumulated chronologically up to the voltage limit of the system. Although such dc voltage was generally small (e.g., 10-15 V), an electric field between the device electrodes reached about 0.5 MV/m due to the very short electrode gap. Therefore, there was the possibility of high field induced damage to the device materials during the long-term operation of the modulators at higher temperature. If a dielectric breakdown was generated in the buffer layer and lithium niobate substrate, not only the dc drift would be accelerated, but also a domain inversion would occur at the lithium niobate surface. Minakata suggested such a possibility based on the experimental data in which a significantly large dc drift was observed in a modulator sample operated with a very high dc bias voltage about ten times greater than the half-wave voltage of the sample.[7] Here, the proposed drift acceleration by the applied voltage was confirmed to be generated at lower operation voltages in the device operated at 130°C. Furthermore, the presence of a domain inversion was found in the lithium niobate waveguides placed under the electrodes.

The Mach-Zehnder type optical waveguide for light wavelength of 1.5 μm was prepared by a titanium diffusion process on the -*z* face of a commercial lithium niobate substrate. The device structure with a 1 μm thick SiO_2 buffer layer and the fabrication conditions were reported in previous articles.[3,6] Further, the 19 μm thick coplanar Au electrodes were fabricated on the thin Si-coated buffer layer.[6] A gap between the hot and ground electrodes was 25 μm and equal to the Mach-Zehnder waveguide gap. The active length of the hot electrode was 40 mm. The half-wave voltage ($V\pi$) of the device was measured as 3.5 V at 1 kHz operation.

Figure 1 shows the operation time dependence of a dc bias voltage applied to the ac ($V_{p\text{-}p} \cong 4$ V, slightly greater than the $V\pi$) driven modulator to maintain the operating point of light-modulation output at the initial dc= +4.5 V biased state (control frequency ≅ 1 kHz). The ac and dc voltages were supplied to the same hot electrode. The temperature was kept at 130°C during the operation. In this follow-up bias control system, the maximum drive voltage was 10 V. The figure revealed that the applied dc bias drifted by at least three stages. Such behavior of the dc drift could be more clearly shown as a change of the dc drift rate in Fig. 2, which was calculated from the data of Fig. 1. During the operation at 130°C, the drift rate kept a positive value except for a very short duration (<1 h) just after the operation was started (not shown in Fig. 2.). The drift rate decreased rapidly during the first 10 h and settled at 20 mV/h, while the applied bias voltage increased to about 6.5 V. However, after the 50 h operation, the drift rate stepped up abruptly to 60 mV/h. As a reason for the switch of drift rate, an overlapping of two different drift phenomena having their own individual relaxation times and driving forces (threshold voltages) could be considered. In this regard, the authors

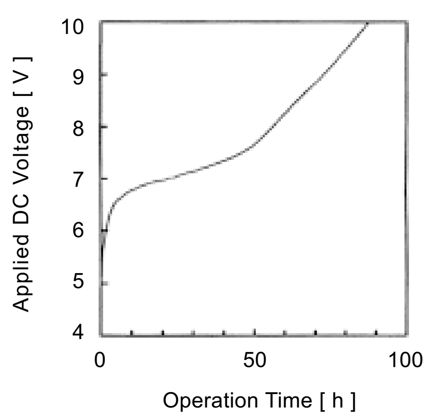

FIG. 1. Result of follow-up bias controlled operation of the modulator at 130∞C with initially applied dc bias of 4.5 V.

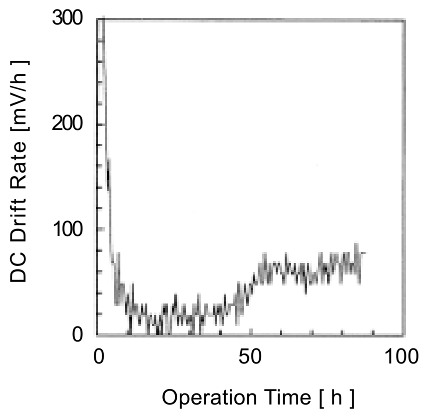

FIG. 2. Relationship between the dc drift rate and the operation time at 130∞C derived from Fig. 1.

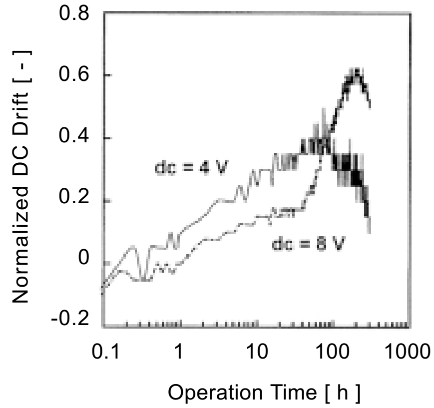

FIG. 4. Normalized dc drift measured by a fixed dc bias method at 130°C.

presupposed the presence of the fast drift induced by higher dc voltage application.

In order to confirm the presumption, the modulators from the same wafer were operated at 130∞C by ac 1 kHz (V_{p-p}=20 V) with an accumulated fixed dc bias voltage of 4 and 8 V. If the higher dc bias application induced the fast drift, the 8 V application would induce it because the kink point of the drift curve in Fig. 1 was about 7.5 V. Figure 3 shows such dc drifts normalized by the applied dc bias of 4 V (white marks) and 8 V (black marks). Here, a time-dependent shift of a specific light-modulation output peak voltage from the initial value was determined to be the dc drift. The drift decelerated gradually within 10 h. Then, the drift on the 4 V applied device seemed to settle until the 80th hour with a gradient of 0.0017. The 8 V applied device drifted similarly until the 45th hour with a gradient of 0.0014. However, the drift rate increased beyond 45 h (the gradient of plots was 0.0049), indicating the presence of drift accelerated by the highly applied dc bias, as expected.

The drift measurements of Fig. 3 were continued for 300 h, as shown in Fig. 4. Except for unexpected negative drifts in both samples beyond 100 h, no abrupt change was observed in the drift rate of the 4 V applied device. The maximum drifts were 40% for the 4 V applied device and 60% for the other device. Such a difference in the maximum drift magnitude supported the presence of the larger drift phenomenon dependent on bias voltage. Concerning the negative drift phenomenon, further investigation was needed.

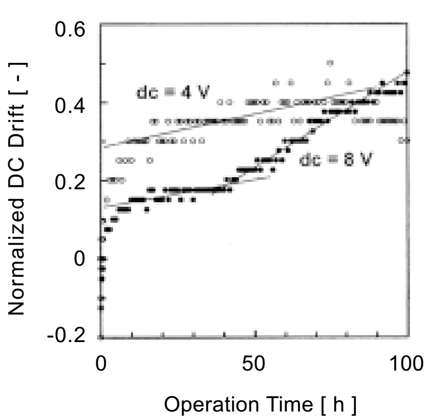

FIG. 3. Normalized dc drift measured by a fixed dc bias method at 130°C.

The modulator chips of Fig. 4 were chemically etched using a HF/HNO_3 mixture at room temperature for about 12 h. Figures 5(a) and 5(b) are the optical micrographs of etched lithium niobate surface for the 4 and 8 V applied samples, respectively. The lengths of the bars in the figures correspond to 50 μm. "H" and "G" in the photographs denote the waveguides placed under the hot and ground electrodes, respectively. A band of black points along the waveguides, which correspond to the region where the domain inversion occurred, was not observed in the unbiased modulator chip. The density of the black points seemed to be high in the 8 V applied sample. Furthermore, they diffused from the hot waveguide to the ground waveguide (b), while in the 4 V applied device, tha domain inversed region was concentrated on the hot waveguide (a). These results suggested that the electric field applied from the hot electrode induced the domain inversion of the lithium niobate waveguides, possibly depending on the magnitude of

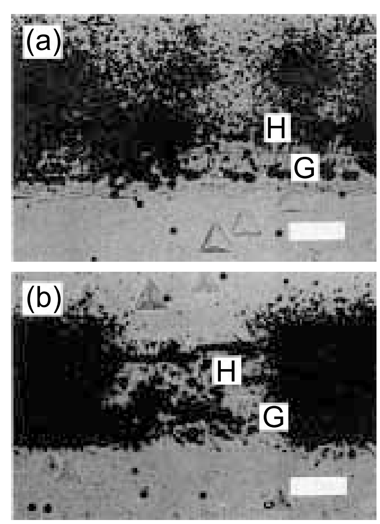

FIG. 5. Optical micrographs of the chemically etched surface of (a) the 4 V applied sample of Fig. 4 and (b) the 8 V applied sample. "H" and "G" denote the waveguide placed under the hot and ground electrodes, respectively. Bars=50 μm.

the field. As a reason for the broadening of the inversed domains over the ground electrode positions, in this instance, an effect of the accumulated ac voltage could be considered because its magnitude was large, $V_{p\text{-}p}$ = 20 V, in the experiment. There was also a possibility that the area at which the dc voltage was supplied was actually extended by a partial current leak through the thin Si layer formed to link the electrodes.

The observed domain inversion was evidence that the dc drift at accelerated conditions was caused by a current leak via the lithium niobate substrate. The results also showed that the higher applied bias voltage caused the acceleration factor of the dc drift, as well as the temperature to rise. The consequent domain inversion at the waveguides was considered to cause an accumulative deterioration of the material, i.e., a fatigue induced by the continuous electric field application. The $V\pi$ of the samples was not changed after the bias application, but a change of on/off extinction ratio became larger in the 8 V applied device of Fig. 4 (- 8.37 ΔdB, while it was +1.74 ΔdB for the other). To investigate an influence of the domain inversion to the device parameter, the cross section of the chip was also chemically etched to observe the inversed domain thickness. However, the boundary of the inversed domains was indistinct, suggesting that the inversed layer was very thin. An investigation of the discussed phenomenon at lower temperatures (≤80C) and the influence of such fatigue on the device characteristics is presently underway.

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