Activation Energy of Dc-Drift of X-Cut $LiNbO_3$ Optical Intensity Modulators

Hirotoshi Nagata

Abstract—**The dc-bias-induced drift phenomenon in $LiNbO_3$ optical intensity modulators is a main cause of device wearout failure. In order to estimate the device lifetime, an activation energy value *Ea* of the drift is needed, and *Ea* = 1.0 eV is already known for z-cut LiNb03 modulators. However, *Ea*, of x-cut $LiNbO_3$ modulators is not known even though there is a possibility that the *Ea* depends on the crystal orientation. Here, *Ea* = 1.4 eV is obtained experimentally for the x-cut $LiNbO_3$ modulator with a SiO_2 buffer layer from their drift measurements between 50°C–140°C.**

Index Terms—**Activation energy, dc drift, $LiNbO_3$ modulators, reliability.**

I. Introduction

THE use of $LiNbO_3$ (LN) optical waveguide modulators is rapidly increasing in optical measurement systems and fiber communication systems. Especially, optical modulators based on z-cut LN crystal exhibit excellent performance such as a lower drive voltage and a broader bandwidth, and have been used as high-speed devices in 10-Gb/s systems. X-cut LN modulators, on the other hand, have unique characteristics in being highly stable in temperature changes and in outputting a zero-chirp signal due to their symmetric device structure. With expanding system demands, the x-cut LN modulators have been also applied to lO-Gb/s systems, although their major use was in 2.5-Gb/s systems [1].

However, both z-cut and x-cut LN modulators, especially in optical intensity modulators, have an inherent problem of dc drift. Due to the dielectric nature of the LN, a dc bias voltage applied to the device to adjust the optical output modulation state reduces gradually, resulting in a drift of optical output state. In order to keep the optical output stable, via a feedback loop, the dc bias is cumulatively applied to the device and ultimately will exceed the limitations of the system driver [2]. In other words, the dc drift is a main cause of wearout failure of LN devices and a reliability risk. Therefore, it is necessary to estimate the device lifetime through biased aging tests on actual devices. The purpose of this letter is to show the activation energy *Ea* of dc drift of x-cut LN modulators, which is necessary to convert the test results done at higher temperatures to results done at ordinary device operation temperatures, 50°C–55°C.

Many experimental results have been reported from independent organizations for the z-cut LN moduiators, and *Ea* was shown to be approximately 1.0 eV [2]-[5]. The smallest *Ea* reported was 0.7 eV [2]. [6], and the highest was 1.4 eV [7]. However, to the author's knowledge, the *Ea*, of x-cut LN modulators has not shown yet. Previously the author suggested the possibility of smaller *Ea*, of x-cut modulators than 1.0 eV of z-cut ones, but the number of samples and the measurement duration to derive the *Ea* was limited, and the result was less reliable [8]. Recent]y, Maack reported longer time measurement data of 2.5 and 10-Gb/s x-cut LN modulators at 85 and 100°C, but the *Ea*, was not given in his report [1].

Manuscript received December 6, 1999; revised December 30, 1999.
The author is with the Optoelectronics Research Division, New Technology Research Laboratories, Sumitomo Osaka Cement Company, Ltd., Chiba 274-8601 , Japan (e-mail: hinagata@sits,soc.cojp).
Publisher Item Identifier S 1041-1135(00)02826-3.

II. Experimental Procedure

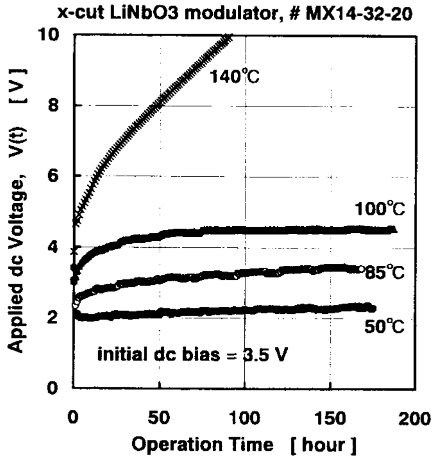
The modulator chips, mainly consisting of a Ti in-diffused Mach-Zehnder waveguide, formed on the *x* face along the *y*-axis an about 1-µm-thick SiO_2 buffer layer by vacuum evaporation deposition followed by oxygen annealing, and a pair of coplanar electrodes. The chip was installed in a stainless steel package and sealed hermetically by soldering fiber insertion ports and seam-welding the package lid.

For the dc drift measurement, all modulator samples were placed in an oven kept at 50°C and operated individually by a followup bias controlled method with the initially applied dc bias of 3.5 V and the optical input of λ = 1.55 µm. In this operation method, the dc voltage applied to each sample was adjusted in a control frequency of 1 kHz in order to maintain the optical output modulation state at the initial state. After the operation at 50°C for about 170 h, the dc bias voltage and the optical input were turned off and the oven temperature was increased to 85 °C. Before the 85°C operation, all samples were aged in the oven without any bias application for more than 170 h to vanish the effect of the previous measurement. In a similar manner, the operation temperature was changed from 50°C to 85°C, 100 °C, 120°C, and 140°C, and the initially applied dc bias was reset to be 3.5 V in each operation.

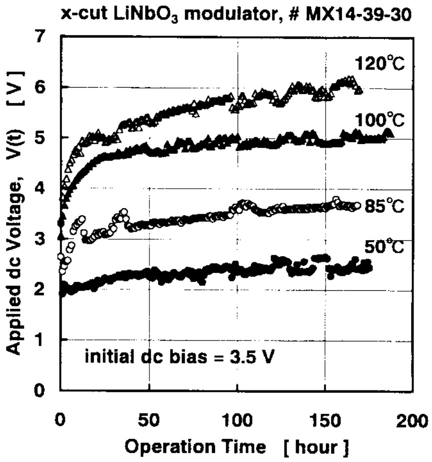
III. Results and Discussion

Fig. 1 shows typical operation results on modulators made from different LN wafers, sample # MX14-32-20 [Fig. 1(a)] and MX14-39-30 [Fig. 1(b)]. The dc drift was found to move toward the negative direction at the early stage and then changed to a positive direction. From the view point of device lifetime, the positive drift, canceling the applied dc bias, is a key and its *Ea*, is needed.

In order to calculate *Ea*, first, a curve fitting of plotted data by a simpler equation was attempted. A relaxation phenomenon of the applied bias in the dielectric materials can be expressed by an equation being proportional to the applied voltage and

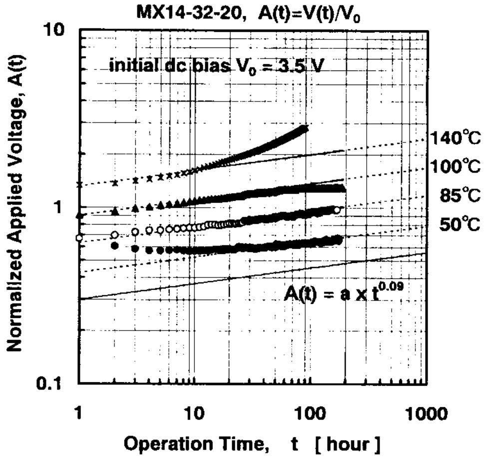


(a)

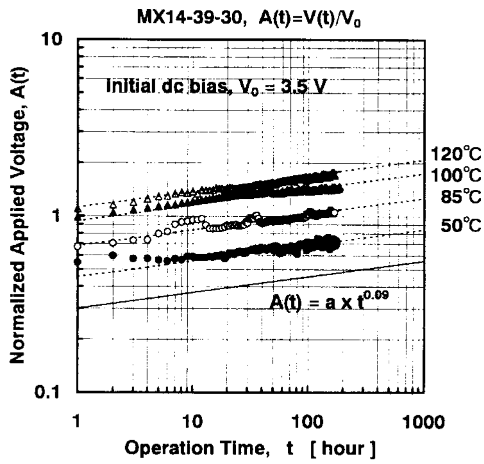


(b)

Fig. 1 . DC drift curves measured on an x-cut $LiNbO_3$ modulator sample (a) MX14-32-20 and (b) MX14-39-30 between 50°C and 140°C with each initial dc bias of 3.5 V. A vertical axis denotes applied dc voltage including the initially applied dc bias voltage, A horizontal axis denotes operation time at the corresponding temperatures. Because the optical input intensity was not so stable in the current test apparatus, some measurement results became irregular and missed the data.



(a)



(b)

Fig, 2. Replots of drift results on (a) MX14-32-20 and (b) MX14-39-30 samples of Fig, 1 . A vertical axis $A(t)$ denotes the applied voltages normalized by the initially applied dc bias of 3.5 V.

the time-dependent term [1– exp (–t / τ)], in which a constant τ is a relaxation time for the material system under consideration [9]. However, in actual device operations, the applied bias is changed continuously, as in Fig. 1, by a follow-up bias controlled method, and the situation gets to be complicated [2], [9]. Recently, the author found experimentally that in the follow-up bias controlled operation of z-cut LN devices, the applied dc voltage V (t) at a certain time t at the constant temperature was almost proportional to the initially applied dc bias $V_0 = V(0)$.

Considering the above empirical information, the following equations:

$$V(t) = A(t) \times V_0 \tag{1}$$

and

$$A(t) = a \times t^{n} = (b \times t)^{n} \tag{2}$$

were used to express the drift curve of Fig. 1 . Here, the index n was expected to be less than one because the drift rate $dV(t)/dt \propto V_0 \times t^{n-1}$ was assumed to decrease during the device operation. Then, the constant b of (2), which was set as a rate coefficient, was assumed to be an Arrhenius-type function of temperature T; i.e., $\mathbf{b} \propto \exp(-Ea / kT)$, a Boltzmann constant $k = 8.62 \times 10^{-5}$ eV/K. The final expression for the assumed equation was

$$V(t) = [\mathrm{B} \times \exp(-Ea / kT) \times t\,]^{n} \times V_0 \quad (0 < n < 1). \tag{3}$$

Fig.2(a) and (b) shows replots of Fig. 1 (a) and (b), respectively, using the above assumptions. The vertical axis denotes the $A(t)$ of (2), in which the measured applied voltage $V(t)$ data was normalized by the initial bias voltage $V_0 = 3.5$V. Most of the data could be expressed by (2) with the same n, almost independent of operation temperature between 50° C–140°C, thus supporting that assumption. However, as is seen, the equation could not express the drift behavior completely throughout all operation duration. The early drift appearing within the first several hours at lower temperatures and the drift highly accelerated by higher temperatures were seen to have different n values. Because the actual operation temperatures were expected to be from 50°C to 65°C, the fitting results (dotted lines of Fig. 2) for the second drift stage were used for the calculation of Ea.

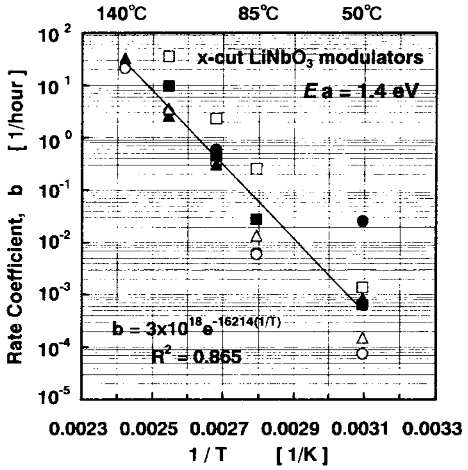


Fig. 3. Arrhenius' plots of all measured drift results, in which the vertical axis is plotted by a calculated rate coefficient *b* (see (2) in the text and Table I). Black circles denote sample MX14-26-14, white circles MX14-32-20, black triangles MX14-39-17. white triangles MX14-39-30. black squares MX14-64-12, and white squares MX14-46-02 samples.

TABLE I

MEASURED AND CALCULATED PARAMETERS ON DC DRIFT OF X-CUT $LiNbO_3$ MODULATORS

Sample number		Index "n"	Rate coefficient "b" [1/hour] at				
Wafer #	Chip #	of $A(t)=(b \times t)^n$	50°C	85°C	100°C	120°C	140°C
MX14-26	-14	0.12	2.55×10^{-2}	6.36×10^{-3}	0.592	3.07	ND
MX14-32	-32	0.09	7.43×10^{-5}	6.00×10^{3}	0.318	ND	21.3
MX14-39	-17	0.09	8.28×10^{-4}	2.81×10^{-2}	0.306	2.63	33.0
	-30	0.09	1.51×10^{-4}	1.38×10^{-2}	0.497	3.56	ND
MX14-61	-12	0.12	6.30×10^{-4}	2.80×10^{-2}	0.456	9.67	ND
MX14-76	-02	0.09	1.36×10^{-3}	0.254	2.30	35.5	ND

The parameter noted by "ND" was not determined due to a measurement error.

Fig. 3 shows the Arrhenius plots on the drift behavior of the tested x-cut LN modulators, in which the rate coefficient *b* of (2) obtained by each of the measurement runs was plotted in the vertical axis. The data used for the plot are listed in Table I. From a gradient of the plots, the activation energy *Ea* = 1.4 eV was obtained. Although attention is needed in the application of high-temperature data such as the 140°C results, the obtained *Ea* value might be used in a wide temperature range from 50 °C to 140°C.

Fig. 4 reveals 330-h-operation results of other x-cut LN modulators with the similar SiO_2 buffer layer at 120°C with the initial dc bias voltage V_0 = 6 V. Because 20 years at 65°C (a common operation temperature) corresponds to 210 h at 120 °C when *Ea* =1.4 eV, the test duration was sufficient to obtain lifetime of devices. Assuming that an initially applied bias of these devices is maximum 6 V, if an end-of life point in driving voltage of the system is set at ±15V, all modulators are expected to work alive through 20 years. In other words, a lot acceptance test of x-cut LN modulators can be completed within nine days at 120°C.

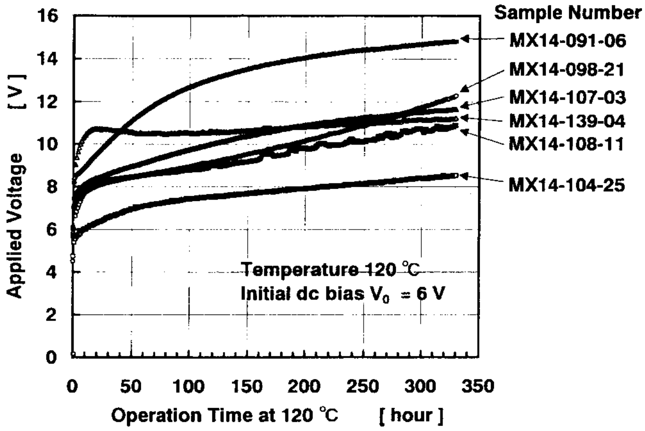


Fig. 4. Example of temperature acce]eration test at 120°C with the initia]ly applied dc bias of 6 V. The samp]es were similar with those of Fig. 1 , but were fabricated by different production batches.

IV. CONCLUSION

The *Ea* = 1.4 eV was obtained on x-cut LN optical intensity modulators with a vacuum evaporation deposited SiO_2 buffer. This *Ea* is larger than I eV typically reported for 10-Gb/s z-cut LN modulators. There is a possibility that a thermal coefficient of electrical characteristics of LN itself depends on the crystal axis. Although the reason for the larger *Ea* in x-cut LN is not clear at this moment, the obtained results is usable to estimate a long-term dc drift behavior for the qualification of the modulators.

ACKNOWLEDGMENT

The author would like to thank K. Akizuki for his help with the dc drift measurements.

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