The Study of Activation Energy(Ea) by Aging and High Temperature Storage for Quartz Resonators' Life Evaluation

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Abstract—**This paper studied the evaluation of activation energy(Ea) based on the experimental data from quartz resonators' biased aging and high temperature storage. 5.0 mm × 3.2 mm metal seam sealed quartz resonators were used in this study. To assure the results are trustable, two approach methods were used for Ea evaluation. The first method is data fit by Arrhenius model for biased aging data. The second method is MTBF evaluation based on high temperature storage data. Both methods conclude the close Ea value, about 0.578eV, and which means 85℃ for 7days accelerated aging is equivalent as 0.83 year at 25℃.**

I. Introduction

For cost and efficiency consideration, electronic device manufacturers usually cannot take a long time room temperature testing for product life evaluation. Instead, most of the electronic devices are through the reliability acceleration tests [1, 2, 3] to estimate the device life. The predominant method to estimate the equivalent life of passive devices is based on Arrhenius's law. Arrhenius proposed the model to describe how temperature affects the materials inter diffusion as following equation.

$$AFT = e^{\left[\frac{Ea}{K_B}\cdot\left(\frac{1}{Tu}-\frac{1}{Ta}\right)\right]} \tag{1}$$

Where AFT is the temperature acceleration factor, which means equivalent life ratio, K_B = 8.616 × 10^{-5}(eV/°K)－Boltzmann's constant, Ta(°K) is the temperature of acceleration environment, Tu(°K) is the device operated temperature, and Ea is the activation energy. The common reliability accelerating temperatures of quartz resonator are 125℃, 105℃ and 85℃. The AFT (or the life estimation) will be affected by Ea value a lot, as shown in Table I. For the quartz resonator's Ea studies, some researches were already done more than 20 years ago [4, 5, 7]. However, the device size and structure changed a lot during past decades. It is necessary to re-evaluate the Ea value for today's quartz crystal resonators. To assure the results are trustable, two approach methods were used for Ea evaluation. The first method is data fit by Arrhenius model for biased aging data. The second method is MTBF evaluation based on high temperature storage data.

TABLE I. Product Activation Energy(Ea) versus Temperature Acclеartion Factor (AFT) at 125℃

T_L(℃)	T_H(℃)	Ea(eV)	K(eV/°K)	Tu(°K)	Ta(°K)	AFT
25	125	0.7000	$8.617*10^{-5}$	298	398	943.17
25	125	0.6000	$8.617*10^{-5}$	298	398	354.53
25	125	0.5000	$8.617*10^{-5}$	298	398	133.26
25	125	0.4000	$8.617*10^{-5}$	298	398	50.09
25	125	0.3000	$8.617*10^{-5}$	298	398	18.83

Like common microelectronic devices, the function of aging frequency change can be expressed as Equation (2) which relates with current, temperature, and time [6]

$$\frac{\Delta f}{f}(i,T,t) = R(i)\cdot R(T)\cdot R(t) \tag{2}$$

For the sake of simplicity, this study we focused on Ea for thermal effect only. Which means we need to minimize the R(i) effect in experiments and neglect it in calculations. 3 elevated temperatures, 85℃, 105℃, 125℃ were selected to make thermal effects stronger, and no room temperature condition in this study. After neglect electrical current effect (or drive level effect), Equation (2) can be re-state as following

$$\frac{\Delta f}{f}(T,t) = R(T)\cdot \ln(1+bt) \tag{3}$$

Where $R(T) = C\cdot e^{\left(\frac{-Ea}{K_B \cdot T}\right)}$, b is constant, and for a specified time, Equation (3) can be expressed as the relationship of frequency change versus to temperature in Equation (4).

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$$\ln\frac{\Delta f}{f} = \ln C - \frac{Ea}{K_B}\cdot\frac{1}{T} \quad (4)$$

II. APPROACH A: ACTIVATION ENERGY FOR AGING TESTING

A. *Aging Experiment*

We took 60 pieces samples for each elevated temperature, 85℃, 105℃, 125℃. 5.0mm × 3.2mm metal seam sealed, 40MHz fundamental quartz crystal resonators were used. Each sample was working in separated oscillation circuit simultaneously. Frequency were measured daily for 1000hrs (about 42days). The results are shown as Fig. 1.

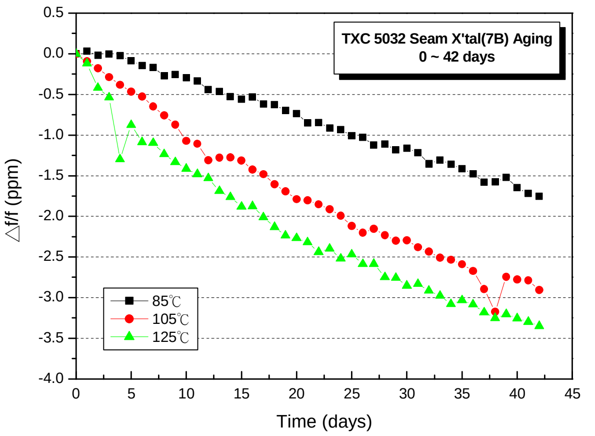

Figure 1. The aging frequency change of 5.0mm × 3.2mm metal sealed quartz resonator for 1000 hrs

TABLE II. EA FIT FROM FIGURE 1 FOR SELECTED DAYS

Days	7	14	21	31	42
Ea	0.578	0.372	0.311	0.270	0.200

B. *Activation Energy Estimation through Arrhenius Prediction Modle*

In Equation (3), if bt >> 1 it can be simplified as Equation (5) and Equation (6).

$$\frac{\Delta f}{f} = R(T)\ln b + R(T)\ln t \quad (5)$$

$$\frac{\Delta f}{f} = C\cdot e^{-\frac{Ea}{K_B\cdot T}}\cdot\ln t \quad (6)$$

For a lower temperature and time, T_L and t_L, we can get the frequency change from Equation (6). Similarly, we can have another frequency change for a higher temperature and time, T_H and t_H.

$$if\ \delta f_L = \frac{\Delta f}{f}(T_L, t_L),\ \text{and}\ \delta f_H = \frac{\Delta f}{f}(T_H, t_H)$$

$$\Delta = \frac{\delta f_H}{\delta f_L} = \frac{\ln t_H}{\ln t_L}\cdot e^{\frac{Ea}{K_B}\left(\frac{1}{T_L}-\frac{1}{T_H}\right)} = \frac{\ln t_H}{\ln t_L}A \quad (7)$$

$$\Delta = \frac{\delta f_H}{\delta f_L} = \frac{\ln t_H}{\ln t_L}\cdot \exp\frac{1}{KB}\left(\frac{1}{TL}-\frac{1}{TH}\right)Ea \quad (8)$$

For now, we can calculate the Δ ratio from Equation (8) by specified Ea, and we can also calculate the Δ ratio from experiment data, and compare these two results to verify the Ea is suitable or not. For T_H=105℃, t_H=7 days, and T_L=85℃, t_L = 7, 14, 21, 31, 42 days, we can get the comparison results as Table III, and the ratio is close when Ea = 0.578 eV.

TABLE III. THE ARRHENIUS VERIFICATION MODEL OF 105℃ VERSUS TO 85℃

105 vs 85 Verification						
	Formula Prediction by Real Ea					Real Ratio
	7	14	21	31	42	NA
Ea	0.578013	0.372427	0.310908	0.269896	0.200391	NA
△7/7	3.212913	2.070151	1.728199	1.500231	1.113883	3.84529
△7/14	2.369043	1.526427	1.274289	1.106196	0.821322	2.411959
△7/21	2.053537	1.32314	1.104581	0.958875	0.71194	2.123997
△7/31	1.820636	1.173076	0.979305	0.850124	0.631195	1.954337
△7/42	1.672711	1.077765	0.899737	0.781052	0.579911	1.655865

We compared different temperature and time conditions (125℃, 7days vs. 105℃, 42days and 105℃, 7days vs. 85℃, 42days) and found the ratio will closest when Ea = 0.578eV as shown in Fig. 2.

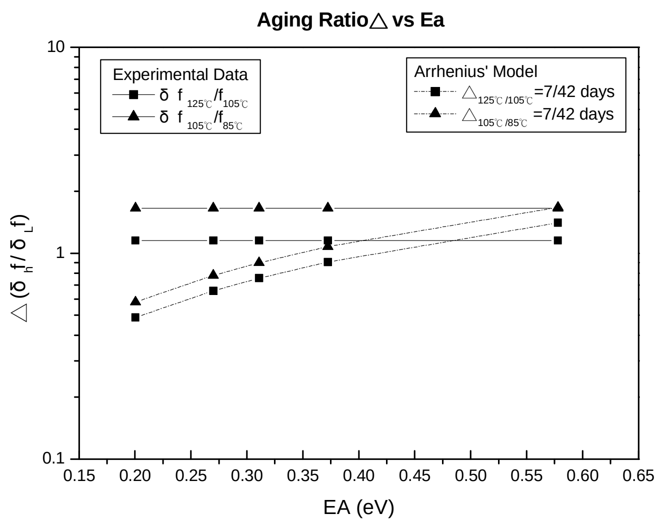

Figure 2. The verification model of 7days at higher tempearure compare to 42days at lower temperature

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III. APPROACH B: ACTIVITION ENGERY BASED ON MTBF ESTIMATION WITH HIGH TEMPERATURE STORAGE DATA

The classical Arrhenius equation show as Equation (9), where t is the time, T is the temperature, replace t as the definition of MTBF in reliability, Equation (9) could further express as Equation (10).

$$\ln t = a + b \cdot \frac{1}{T} \tag{9}$$

$$\ln(MTBF) = \ln\left(\frac{n \times t}{r}\right) = \frac{Ea}{K_B} \cdot \frac{1}{T} \tag{10}$$

Where n is the sample number, t is the experimental time, r is the number of failure device. TABLE IV is the experimental results of high temperature storage [8]. The failure number could be calculated by various device specification, but the meaningful MTBF must satisfied the normal electronics device's failure principle, which means the failure number should between 1 and total samples. Based on it, we selected the blue area as meaningful MTBF area and used as Ea estimation. The results were showed as Table V, the average Ea is 0.569, which is close to 0.578 as estimated by approach A. Because high temperature storage had only thermal effect, no drive level effect inside, and the Ea is close to elevated temperature biased aging test, it can also show thermal effect is dominate in elevated high temperature biased aging.

TABLE IV. THE FAILURE NOMBER OF DIFFERENT DEVICE SPECIFICATION FOR HIGH TEMPEERATURE STORAGE

Temp (℃)	Device Houre (hr)			Failure Number						
	Samples	Time(H)	Total Time	±4ppm ±4ohm	±4.5ppm ±4.5ohm	±4.8ppm ±4.8ohm	±5ppm ±5ohm	±5.5ppm ±5.5ohm	±5.8ppm ±5.8ohm	±6ppm ±6ohm
85℃	30	1074	32220	18	8	**1**	**1**	**0**	**0**	0
105℃	30	1074	32220	30	26	**20**	**18**	**6**	**2**	0
125℃	30	1074	32220	30	28	**26**	**25**	**20**	**15**	11
150℃	30	1074	32220	30	30	**29**	**27**	**21**	**20**	14
85℃	30	1921	57630	30	25	19	15	4	**1**	**1**
105℃	30	1921	57630	30	29	29	29	21	**14**	**10**
125℃	30	1921	57630	29	29	29	27	19	**16**	**12**
150℃	30	1921	57630	30	30	29	29	25	**22**	**16**

TABLE V. THE AVERAGED EA OF HIGH TEMPERATURE STORAGE IS 0.569(EV)

Ea(eV)					
±4.5ppm ±4.5ohm	±4.8ppm ±4.8ohm	±5ppm ±5ohm	±5.5ppm ±5.5ohm	±5.8ppm ±5.8ohm	±6ppm ±6ohm
	0.6313	**0.6220**	**0.3767**	**0.6946**	
				0.5735	**0.5180**
Average = 0.5693					

IV. CONCLUSION

We studied the evaluation of activation energy (Ea) based on the experimental data from quartz resonators' biased aging and high temperature storage. 5.0 mm × 3.2 mm metal seam sealed quartz resonators with fundamental frequency 40MHz were used in this study. To avoid the interference between thermal and drive level effect, we selected 3 elevated temperatures in aging test. To assure the results are trustable, two approach methods were used for Ea evaluation. The first method is data fit by Arrhenius model for biased aging data. The second method is MTBF evaluation based on high temperature storage data. Both methods conclude the close Ea value, about 0.578eV (for thermal effect), and which means 85℃ for 7days accelerated aging is equivalent as 0.83 year at 25℃. The aging mechanism and the effects by drive level or other factors still need more studies in the future.

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