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Stretched exponential degradation of oxide cathodes

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Abstract

In this study, the degradation behavior of oxide cathodes for cathode ray tubes (CRTs) is described using the stretched exponential model, which has been successfully used to describe the dynamics of complex systems characterized by heterogeneity. We derive a longevity equation from the two parameters: (i) characteristic life and (ii) heterogeneity parameter, which characterize the stretched exponential model. From the temperature dependences of the two parameters in the longevity equation, we reveal that the longevity follows the Arrhenius relation in oxide cathodes. The longevity equation and the Arrhenius relation enable us to predict the longevity in early life. The stretched exponential degradation is explained based on the heterogeneity of oxide cathodes.

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Keywords: Oxide cathodes; Stretched exponential; Longevity; Heterogeneity

1. Introduction

Oxide cathodes have been studied for a century, since developed by Wehnelt in 1904 [1], as essential electron sources for cathode ray tubes (CRTs) [2], microwave amplifiers [3], and discharge lamps [4]. However, general mathematical model of emission degradation curves for oxide cathodes has not been given in spite of many emission theories [5–9]. Recently, Weon et al. applied the Weibull model to the degradation behavior of oxide cathodes in terms of reliability engineering [10–12]. The mathematical formulas of the Weibull and the stretched exponential models are identical, but the physical insight is different. We suggest that the stretched exponential model be more appropriate than the Weibull model to understand the degradation behavior of oxide cathodes because the former effectively represents the dynamics of complex interactive processes based on the heterogeneity [13].

We derive a longevity equation from the two parameters: (i) characteristic life and (ii) heterogeneity parameter, which characterize the stretched exponential model [13]. Temperature as one of

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degradation factors can significantly affect the two parameters and in turn the longevity. From the temperature dependence of the two parameters in the longevity equation, we reveal that the longevity follows the Arrhenius relation in oxide cathodes. The longevity equation and the Arrhenius relation enable us to estimate a reliable prediction of longevity (~5 years) of oxide cathodes in a short-term period of tests (~500 h). It will be discussed that the stretched exponential degradation is based on the heterogeneity of oxide cathodes.

2. Stretched exponential model

The stretched exponential or Kohlrausch–Williams–Watts model was first studied as empirical descriptions for the structure relaxation of glassy fibers by Kohlrausch in 1847 [14] and again for the dielectric relaxation in polymers by Williams and Watts in 1970 [15]. So far, this model has been successfully used to describe the short-term decay dynamics of various complex systems (for instance, see [13,16,17]). Recently, it was reported that the stretched exponential model could describe the degradation behaviors of electroluminescence (EL) devices for several hundred hours [18]. However, the application of the stretched exponential model to degradation behaviors of other applications for a long period of time (~several years) has yet to be studied.

Consider a general question about how a system decays over time. Even though the active state, function, performance, and/or the number of survivors in a system naturally progress, they should decay over time in the end. In this case, we believe that there would be a universal law in degradation pattern. The simple exponential model is often used as a universal decay model but this is valid only if a homogeneous (single) exponential mechanism is predominant. The stretched exponential model is more general than the simple exponential model [13,16,17]. The performance P, which decays over time, for example, the normalized emission current of oxide cathodes, can be described by the stretched exponential model as follows [16–18]:

$$P = \exp\left(-\left(\frac{t}{\alpha}\right)^{\beta}\right) \tag{1}$$

where t is the degradation time, and α and β denote the characteristic life (or the scale parameter, always indicating the time for $P = \exp(-1)$) and the stretching factor (or the shape parameter), respectively. Sometimes the reciprocal of β is defined as heterogeneity parameter h ($=\beta^{-1}$) [13,16], which gives an insight of heterogeneity in complex systems. At $h = 1$, the decay curve consists of homogeneous exponential term (single mechanism), while at $h > 1$, the decay curve consists of heterogeneous exponential terms (multiple mechanisms).

To use the stretched exponential model, we need to know how to estimate the two parameters in the stretched exponential model. The two parameters "α and β (or h)" can be evaluated from the straightness of "$\ln(-\ln P) = \beta \ln t - \beta \ln \alpha$" of degradation data. In practice, the slope (s) indicates β (or $\beta = s$) and the intercept (i) is a function of α and β (or $\alpha = \exp(-ih)$). On the other hand, it is essential to identify the effects of degradation factors (e.g., temperature, voltage, or humidity) on the longevity in order to understand the degradation processes and to predict the longevity [19].

It is very useful, if we are able to know the mathematical relationship between the longevity and the two parameters of the stretched exponential model. The longevity l can be defined as the time at which the performance P reaches a specific failure level. From the mathematical form of $-\ln P = (t/\alpha)^{\beta}$ in Eq. (1), a general equation of the longevity l is simply derived as follows:

$$l = \alpha\mu^{h} \tag{2}$$

where μ is a natural logarithmic value of the performance ($-\ln P$) corresponding to a failure level (e.g., $-\ln 0.5$ for a half-life). This longevity equation is always valid for $h > 0$ and can be described as the longevity of the simple exponential model, $l = \alpha\mu$, for $h = 1$. Note that the longevity l can be evaluated in early life, based on the two parameters α and h values that are estimated by the experimental observation.

3. Experimental results

First, we discuss the degradation behavior of the oxide cathodes which operated at a normal temperature of 1080 K for 25,000 h (~3 years) in the real tubes of