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Oxide Cathodes for Reliable Electron Sources

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Abstract

In this paper, we investigate the oxide cathodes for the development of reliable electron sources. Poisoning in oxide cathodes is one of the serious problems in achieving reliable electron emission. In particular, early poisoning induces poor life performance as will be demonstrated herein. The survivability of electron emission sources is significantly improved by high doping of high-speed activator. The robust oxide cathodes with 0.17 % Mg operating at about 1,050 K are expected to work for very long times (>100,000 hours). We suggest that this key idea will contribute to solving the basic problems in oxide cathodes such as poisoning or ion bombardment for high power or high frequency applications of electron sources.

Keywords : oxide cathodes, electron sources, poisoning, robustness

1. Introduction

Cathode is one of the most important parts in electron devices that use free electrons [1]. When thermionic emission is applied, the cathode material must have low work function and high melting point to avoid significant evaporation at working temperature [1]. The two main types of thermionic cathodes are oxide and dispenser cathodes [2]. Oxide cathodes, since they were first discovered by Wehnelt in 1904 [3], have played an important role in modern physics [4] and are still fascinating as economical electron sources for various applications [5-12].

The advantages of oxide cathodes are their simple manufacture, high current densities (~ 5 A/cm^2 under a dc load), together with low working temperatures (900-1,100 K) due to their low work functions (~ 1 eV) [1,13]. However, because of their sensitivity to ion bombardment and susceptibility to poisoning at working temperature [1,13] their use is restricted to advanced applications such as free electron sources for electron accelerators [6]. Specifically, the poisoning problem, which is caused by residual gases (e.g., O_2, CO, Cl, etc.) and water vapor at room temperature, can drastically decrease both the thermionic emission and the electrical conductivity in oxide cathodes [14]. The ion bombardment, which can also be induced by the residual gases, restricts high power or high frequency applications of oxide cathodes.

The oxygen poisoning mechanisms that are associated with the reduction of electron emission in oxide cathodes have long been studied [14-21]. Indeed, the poisoning in early life significantly affects the entire life performance of oxide cathodes [21]. For this reason, the sealed-off tubes should be always be maintained at a high vacuum of 10^{-7} ~ 10^{-8} Torr, which could reach an ultra high vacuum of ~ 10^{-10} Torr after long periods of operation by the getter action in the vacuum tube [13,20]. Due to this reason, the vacuum pressure must not be poorer than 10^{-6} Torr in practice [13]. The applications of oxide cathodes to advanced devices seem to be inadequate yet because of their frailty to poisoning or ion bombardment [1]. One important task to be accomplished is, therefore, to develop new oxide cathodes that can solve the serious problems of poisoning or ion bombardment induced by the residual gases.

Therefore, the primary aim of this study is to develop new robust oxide cathodes that can tolerate severe poisoning ambience (>10^{-6} Torr) especially in early life for reliable life performance. We will show that the survivability of the new oxide cathodes is improved by enhancing recovery rate

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against poisoning rate using high-speed activator. The poisoning-recovery dynamics in the oxide cathodes is discussed with the predator-prey model. The fast recovery concept using the robust oxide cathodes developed here may contribute to solving the basic problems such as poisoning or ion bombardment for high power or high frequency applications of oxide cathodes as advanced electron sources.

2. Experiments

The new robust oxide cathodes consist of triple oxides (Ba-Sr-Ca) emitter, in which 30 ppm yttrium (Y) is doped to enhance electrical conductivity. The triple oxides $(Ba_{0.45}Sr_{0.45}Ca_{0.1})O$ are converted from the metal carbonate powders which are prepared from the co-precipitation of $(NH_4)_2CO_3$ and $(Ba,Sr,Ca)(NO_3)_2$ aqueous solution. 3.87 % tungsten (W) and 0.17 % magnesium (Mg) are contained as activators in nickel (Ni) base metal. The development of the new robust oxide cathodes is based on a novel idea of Gaertner *et al.* [21] and old findings on the activity and the diffusivity of many activators in Ni base metal [22-26], as well as on our recent understandings of electron physics of oxide cathodes [27-29].

Mg is known to be the best active, high-speed activator in Ni base metal [13,22-26]. Gaertner *et al.* demonstrated that Mg activator can be used for robust oxide cathodes to overcome the oxygen poisoning using ideal UHV chamber [21]. With this in mind, we attempted to increase the concentration of Mg in the Ni base metal in order to facilitate the new oxide cathodes to overcome the real gas poisoning in real tubes instead of using ideal UHV chamber. Assuming that the fast diffusion rate of Mg could fasten the recovery rate of oxide cathodes against the attack rate of residual gaseous molecules (poisoning or ion bombardment), we increased the amount of Mg to 0.17 % for the new cathodes whereas the Mg content is typically 0.05 % in conventional cathodes. In this study, we used relatively high concentrations of Mg in the Ni base metal for the new oxide cathodes.

The outline of the experimental details is as follows. We first prepared both of conventional oxide cathodes and robust oxide cathodes, and they were applied to electron guns for cathode ray tubes. All testing cathodes, guns, and tubes except new base metals were fabricated by LG. Philips Displays. The conventional base metal contains 0.05 % Mg and 0.05 % Si, but the new base metal 0.17 % Mg and 3.87 % W for the robust oxide cathodes. The main difference in the base metal is the Mg contents as 0.05 % Mg (*conventional*) and 0.17 % Mg (*new*). The other elements such as Y, Si, and/or W have little effect on the emission performance and the poisoning dynamics, as will be discussed in the next section. Actually Mg is known to be the most active, high-speed activator in oxide cathodes [13, 22-26]. We mainly focused on the difference in the Mg content in view of robustness against poisoning. The new base metals for our experiments were supplied from Tokyo Cathode Laboratory.

We prepared the testing tubes that were used to provide the severe poisoning ambience by controlling the exhaustion processes. We measured the total vacuum pressure during life tests in the real tubes using the well-known, non-destructive method (the so-called Gas Ratio [GR] test in CRTs [30]). The GR measurement in Fig. 1 was carried out at a constant beam current (dc) of Ik = 500 μA which was adjusted by the grid-1 voltage (Eg1). The grid-2 (accelerator) and the grid-3 (collector) voltages were 200 V (Eg2) and -25 (Eg3) respectively, and the heater voltage (Ef) was 6.3 V, which is corresponding to 1,050 K. The ion current, Ig3, was measured at the grid-3. The value of GR (=Ig3/Ik) indirectly counts the number of ionized particles generated between electron beam and neutral particles in vacuum. The principle of GR test is identical with that of ionization vacuum gauge. We also conducted the life tests as in Fig. 2 by measuring the emission current change with time, I(t)/I(0), for 1,000 hours, when the oxide

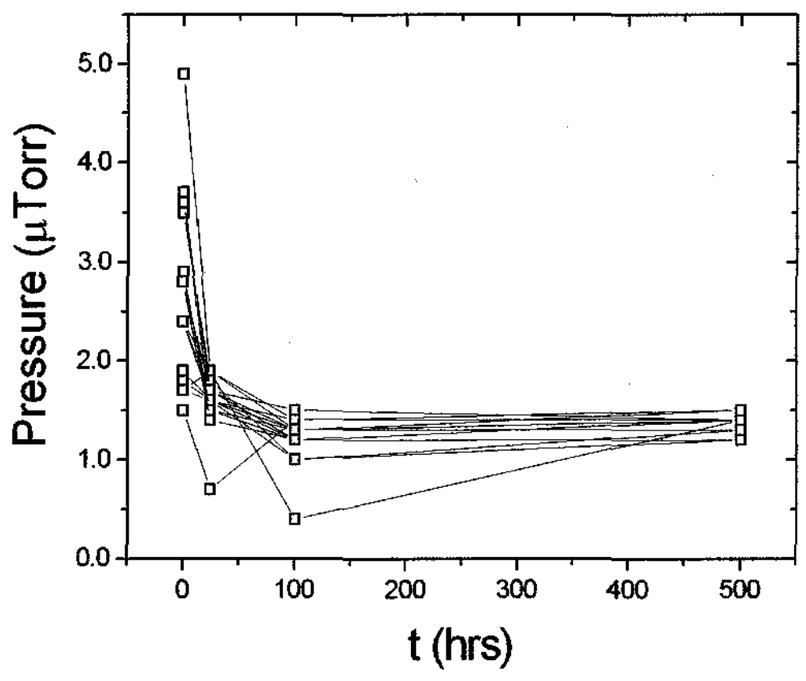

Fig. 1. Poisoning ambience in early life. The poisoning ambience for 100 hours exceeds ~ μTorr (~ 10^{-6} Torr) in testing tubes.

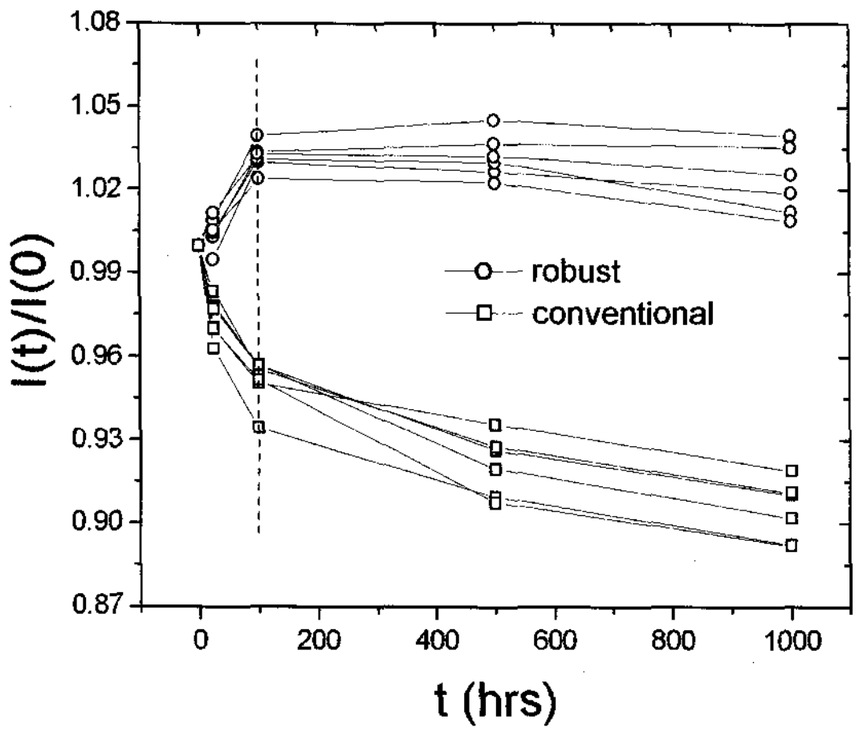

Fig. 2. Life performance of conventional oxide cathodes operated for a period of 1,000 hours. The life performance of the conventional oxide cathodes for 1,000 hours (open squires) is significantly affected by the initial poisoning, especially during the first 100 hours (dashed line). However, the robust oxide cathodes are invariant to the initial poisoning effect (open circles) with very little decay.

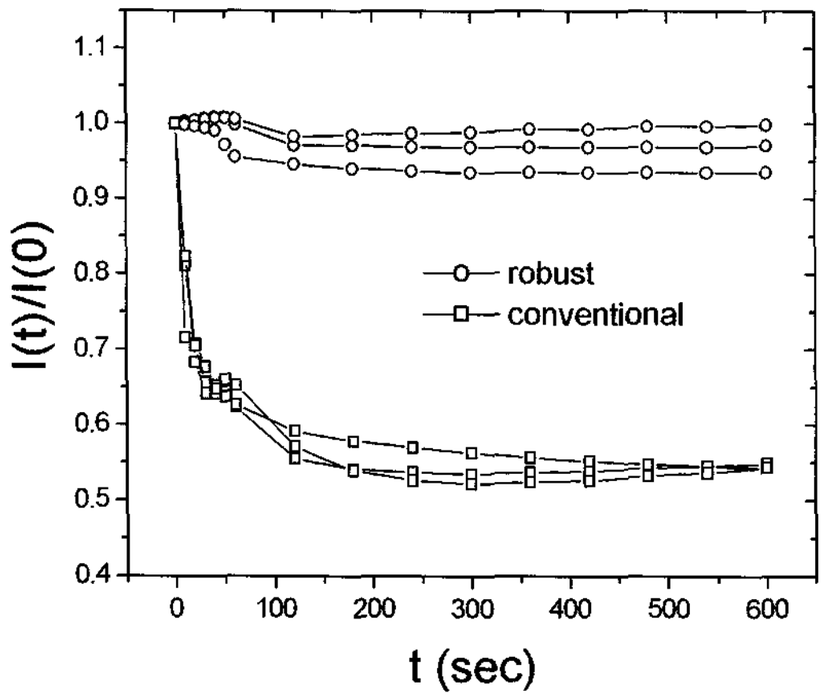

Fig. 3. Self-poisoning (or self-ion bombardment) test. The robust oxide cathodes (open circles) are more resistive against poisoning than the conventional oxide cathodes (open squires).

time. The self-poisoning effect becomes more significant at lower temperatures. Such conditions induce the rush of ionized particles in vacuum and cause the significant attack of residual gaseous molecules onto the cathode surface.

3. Results and Discussion

In this section, we will discuss the experimental results in terms of emission performance. Obviously, the poisoning ambience in early life before 100 hours exceeds μTorr (10^{-6} Torr) in the testing tubes, as shown in Fig. 1. In the initial poisoning ambience, Ar gas remains as the main gas component, followed by N_2, CO, and CH_4 gases, which were measured by RGA tests. Particularly, CH_4 gas is believed to be the most poisonous gas for our oxide cathodes, because it changes the chemical states of the cathode surface [20]. After 100 hours, the poisoning ambience decreases because of the latent action of getters in the testing tubes. We found that the severe poisoning ambience consisting of Ar, N_2, CO, and CH_4 gases in early life induces inevitably the significant emission degradation, as shown in Fig. 2. Their life performance in the conventional oxide cathodes for period of 1,000 hours (open squires) is significantly affected by the early poisoning history (Fig. 1), especially during the first 100 hours (dashed line). The life performance of the conventional oxide cathodes is very poor. However, the robust oxide cathodes are invariant to the initial poisoning effect (open circles), showing little decay in the life performance. This means that the robust oxide cathodes are able to be highly reliable to withstand the poisoning effect in early life and that the robust oxide cathodes are more resistive against poisoning than the conventional oxide cathodes.

From the results of the self-poisoning experiments, as shown in Fig. 3, we can conclude that the enhancement of the resistance against poisoning improved the life performance of the robust oxide cathodes in Fig. 2. This confirms that the more addition of the high-speed activator such as Mg does increase the survivability of cathodes, because the fast recovery rate overcomes the attack rate of residual gaseous molecules in early life.

Now, let us examine the poisoning-recovery dynamics for oxide cathodes in view of the predator-prey model [31,32]. The poisoning-recovery dynamics can be described

cathodes operated at a temperature of 1,100 K (Ef = 6.9 V) with the initial current density (dc) of 5.0 A/cm^2 on average. Next, we conducted the self-poisoning experiments. We modified the above non-destructive GR test, where we evaluated in Fig. 3 the effect of self-poisoning on emission performance by measuring the emission current change at very short times during the self-poisoning conditions: Ik = 500 μA, Eg2 = 100 V, Eg3 = -25 V, and Ef = 5.0 V (corresponding to 850 K). The Ig3 (dc) was measured with

as continuous competitions between the poisoning and the recovery rates on the cathode surface, even though the complicated processes are involved in the actual phenomena [27-29]. Let us think of the two rates; (i) *poisoning rate*: the residual gaseous molecules (predator) attack the emission sources (prey) on the cathode surface and (ii) *recovery rate*: the activators regenerate and re-supply the emission sources to withstand the poisonous attacks. The numerical dynamics can be expressed as follows: $s(t) = \sum (r(t)-p(t))$, where s(t) denotes the survival rate of the emission sources such as free Ba on the cathode surface [27], r(t) the recovery rate by the activators, and p(t) the poisoning rate of the attack gases. The summation, $\sum$, implies the ensemble effect. In the robust oxide cathodes the main role of Mg enhances the recovery rate by activating free Ba generation at the oxide-base metal interface by the high-speed activation of Mg. We also note that Mg atoms did not reduce the work function, even though they were diffused into the cathode surface (data not shown). If one rate is predominant to another rate, the survival rate can be described by the predominant rate. However, the competition between the two rates is likely to appear as a typical chaotic dynamics, which is similar to that observed in the predator-prey model [31,32]. We note that in Fig. 3, the poisoning behaviors do not follow the simple exponential dynamics, but seem to follow the flexible stretched exponential dynamics [33]. Fundamentally, the complex dynamic behavior of the poisoning-recovery dynamics is attributed to the competition mechanism of the poisoning and the recovery rates, as described in the predator-prey model.

The fast diffusion rate of Mg is responsible for the fast recovery rate to overcome the attack rate of residual gaseous molecules. However, we note that the content of Mg more than 0.17 % can reduce the life performance because leakage current is generated between the cathode and the electrode by evaporation or ion bombardment of Mg diffusing into the cathode surface. The robust oxide cathodes with 0.17 % Mg operating at normal temperature (~ 1,050 K) are expected to work for very long times (>100,000 hours), compared with the lifetime of the conventional oxide cathodes [29] that suffer from severe initial poisoning at ~ 10^{-6} Torr. Of course, a more reliable emission performance would be expected under a better vacuum quality.

4. Conclusions

In this study, we developed new robust oxide cathodes for reliable electron sources. We observed that the poor life performance is induced by the early poisoning effect in oxide cathodes. We showed that the survivability of oxide cathodes is improved by enhancing the recovery rate against poisoning rate when high-speed activator was used and the excellent robustness against poisoning is due to the fast recovery rate by high-speed activator. We also found that the development of the robust oxide cathodes could be achieved by increasing the concentration of the high-speed activator, Mg, in Ni base metal. The poisoning-recovery dynamics for oxide cathodes was discussed in view of the predator-prey model. We expect that the fast recovery concept using the robust oxide cathodes as introduced herein will contribute to solving the basic problems such as poisoning or ion bombardment for high power or high frequency applications of advanced electron sources.

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