Study of PCB Bonding Finger Surface Discoloration

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Abstract The phenomenon of printed circuit board (PCB) bonding finger surface discoloration was explained by analyzing the diffusion of copper atoms，that was, the copper atoms diffused from copper substrate to PCB bonding finger surface, then was oxidized. At the same time, the inherent driving force of copper atoms diffusion in the PCB bonding finger was analyzed. In addition, the diffusion flux and concentration distribution expressions of copper atoms in the PCB bonding finger were drawn by analyzing Fick's Law combined with actual conditions, which provided a theoretical basis for preventing diffusion of copper atoms in the PCB bonding finger.

Key words bonding finger; concentration distribution; diffusion flux; discoloration; PCB

PCB金手指表面变色研究

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【摘要】对印制电路板(PCB)金手指表面变色进行研究，通过对铜原子扩散的分析，解释了PCB金手指表面变色的原因，即铜原子扩散到PCB金手指表面而被氧化；另外，通过分析铜原子在PCB金手指表面的扩散的内在驱动力，并利用菲克定律结合实际条件得出铜在PCB金手指表面的扩散流量和浓度分布表达式，为在实际运用中防止铜原子在PCB金手指表面的扩散提供了理论依据。

关 键 词 金手指；浓度分布；扩散流量；变色；印制电路板
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The printed circuit board (PCB) bonding finger[1] acts as electrical connection interface to a the crucial role in the PCB electrical conduction. The production process of the PCB bonding finger was that a thin gold layer (no more than 0.1 μm) was electroplated on the surface of the copper layer in order to reduce the contact resistance, enhance the mechanical properties of interface and prevent oxidation[2-3]. So the production and maintenance of PCB bonding finger must be required carefully due to its important role. Nevertheless, no matter how careful operation was, the color of gilded surface was always darkened, which seriously affected the reliability of electronic equipment. Normal gold surface and abnormal gold surface photos are shown in Fig. 1 and Fig. 2, respectively.

Fig. 1 Normal gold surface

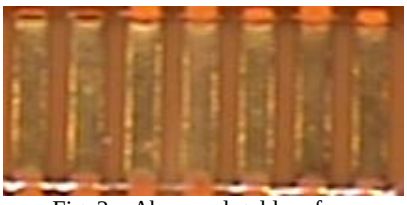

Fig. 2 Abnormal gold surface

The darkened surface of PCB bonding finger was due to surface oxidation[4-5]. On account of gold's inactive chemical property, it always existed in the form of free in nature, therefore, gold was not oxidized

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under normal circumstances. In view of very thin bonding finger (no more than 0.1 μm) and gap in the gold layer, the PCB bonding finger discoloration mainly attributed to diffusion of copper atoms from copper substrate to gold layer, which could be confirmed by the elements analysis of the PCB bonding finger surface. Owing to the difference of electrical potential between copper substrate and gold layer, the copper atoms of diffusion were corroded when encountering with the corrosive medium[6-7]. So the PCB bonding finger was discolored when the corrosion of copper gathered on the gold layer surface. For the time being, the key question was what the driving force of copper atoms diffusion was. This paper analyzed the inherent driving force of copper atoms, that was, the atomic diffusion energy, and drew the diffusion flux and concentration distribution expression of copper atoms in the PCB bonding finger.

1 Inherent Driving Force of Copper Atoms Diffusion

It is well known that all the atoms were in a state of incessant, random thermal motion. The so-called diffusion was external manifestation of atomic thermal motion, that was, atoms were transferred from one part of the system to another. Copper was a crystal[8], so copper atoms were arranged in accordance with the certain geometric shape. The specific form of atomic arrangement was commonly referred to the crystal lattice in crystal，and crystal cell was used to describe the smallest periodical unit in the crystal lattice. Copper crystal cell was the face-centered cubic lattice structure. Fig. 3 shows six copper atoms in the six face centers.

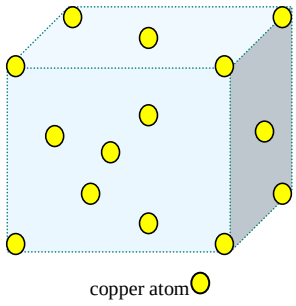

Fig. 3 Copper crystal cell

Copper crystal lattice was the equilibrium position of atoms，that is, all the atoms were in a state of incessant random thermal motion around the lattice. The combination of great deal of atomic energy (kinetic energy and potential energy of copper atoms) was the inherent driving force of copper atoms diffusion[9]. According to the actual situation of copper atoms in PCB bonding finger, the copper atoms should diffuse upwardly along the vertical direction in the PCB bonding finger, as can be considered that the diffusion direction was one-dimensional[10]. So the total energy of copper atoms was studied in this case, including atomic kinetic energy and potential energy. because copper atoms energy was the main driving force of diffusion in the PCB bonding finger[10].

If the copper crystal has N atoms under the PCB bonding finger, the equilibrium position of copper atom in the crystal lattice was expressed by R_n, the displacement of copper atom vibrating from the equilibrium position was expressed by $U_0(t)$,the actual position of copper atom was expressed by R_n', we have:

$$R_n' = R_n + U_0(t) \tag{1}$$

In Eq. (1), $U_0(t)$ was a displacement vector which was often expressed by three respective vectors along the Cartesian coordinate system. In order to facilitate the study, the total system potential energy of N copper atoms was expressed by Taylor series expansion near the equilibrium position expressed in Eq. (2), only along the vertical direction:

$$V=V_0+\sum_{i\,i=1}^{N}\left(\frac{\partial V}{\partial U_i}\right)_0 U_i + \frac{1}{2}\sum_{i=1}^{N}\left(\frac{\partial^2 V}{\partial U_i^2}\right)_0 U_i^2 + \text{higher order term } \cdots \tag{2}$$

In Eq. (2),the subscript mark “0” expressed value of copper atoms potential energy in the equilibrium position, as long as selecting equilibrium position as reference point of zero potential energy, it can be drawn:V_0=0, $\left(\frac{\partial V}{\partial U_i}\right)_0$ =0. System potential energy function should be retained only the quadratic term of U_i, because harmonic approximation was generally taken to handle small vibration issue of atom. So higher order term were omitted. Finally, the potential energy function is expressed as follows:

$$V=\frac{1}{2}\sum_{i=1}^{N}\left(\frac{\partial^2 V}{\partial U_i^2}\right)_0 U_i^2 \tag{3}$$

The kinetic energy function of the N atoms system was expressed as follows:

$$T=\frac{1}{2}\sum_{i=1}^{N}m_i v_i^2 \tag{4}$$

Then the total energy E can be got:

$$E=V+T \tag{5}$$

The expressions of copper atoms kinetic energy and potential energy were drawn for the purpose of clearer understanding of copper atoms diffusion, which were the inherent driving force of atomic diffusion. Nevertheless, this expression is rather complicated, canonical coordinates system can be introduced to simplify the problem, but this paper only described the driving force of copper atoms, so there is no need for further analysis of expression. In addition, the external manifestation of inherent driving force of atomic diffusion is the diffusion flux and concentration distribution of copper atoms in the PCB bonding finger, which described from the macroscopic view by Fick's First Law combined with actual conditions.

2 Diffusion Flux and Concentration Distribution of Copper Atoms in the PCB Bonding Finger

Fick's First Law[11]: diffusion mass through per unit area in unit time is proportional to the concentration gradient of vertical cross-section direction expressed as follows:

$$J=\frac{\mathrm{d}m}{\mathrm{d}t}=-D\frac{\partial C}{\partial x} \tag{6}$$

where J is diffusion mass，kg/(m^2 s) or g/(cm^2 s); C is diffusion mass concentration, kg/m^3 or g/cm^3; x is space coordinate of vertical cross-section direction, m or cm; D is diffusion coefficient, cm^2/s or m^2/s.

The negative sign expresseed that diffusion direction was opposite with concentration gradient, that is, diffusion got along with the reducing direction of concentration. Because of the thin gold-plated layer (no more than 0.1 μm), copper atoms diffusion belonged to steady-state diffusion in the PCB bonding finger, that was, diffusion mass concentration did not change in all of the system points during the diffusion process:

$$\frac{\partial C}{\partial t}=0 \tag{7}$$

where C is diffusion mass concentration, and t is diffusion time.

So diffusion mass concentration gradient did not change in all of the system points during the steady-state diffusion process:

$$\left(\frac{\partial C}{\partial Z}\right)_Z=\text{Const.} \tag{8}$$

Where Z is the coordinate of vertical direction, so it can be drawn that diffusion flux did not change in all of the system points expressed as:

$$J_Z=\frac{\mathrm{d}m}{\mathrm{d}t}=-D\left(\frac{\partial C}{\partial Z}\right)_Z=\text{Const.} \tag{9}$$

Therefore copper atoms diffusion can be described by the Fick's First Law combined with actual conditions in the PCB bonding finger. Because PCB bonding finger was generally cuboid in shape, cuboid is introduced as a model to study the diffusion flux in the PCB bonding finger. Fig. 4 shows the length a, width b and height L of the PCB bonding finger.

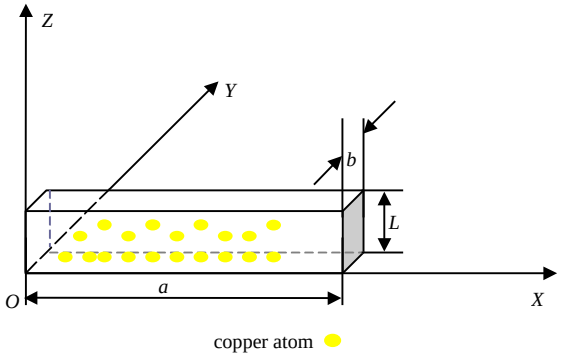

Fig. 4　Model of PCB bonding finger

Diffusion flux don't change in all of the system points in the PCB bonding finger, which was expressed as follows:

$$J_A=-D\left(\frac{\mathrm{d}C}{\mathrm{d}Z}\right)ab \tag{10}$$

where A is the cross-sectional area. Transposition and arrangement were expressed as follows:

$$J_A\,\mathrm{d}Z=-Dab\,\mathrm{d}C \tag{11}$$

If diffusion coefficient was a constant, each side of this equation was integrated expressed as follows:

$$\int_0^L J_A\mathrm{d}Z=-\int_{C_0}^{C_L}Dab\mathrm{d}C \tag{12}$$

$$J_AL=-Dab\,(C_L-C_0) \tag{13}$$

where C_L is copper atoms concentration of upper

surface in the PCB bonding finger, C_0 is copper atoms concentration of undersurface in the PCB bonding finger.

Diffusion flow through PCB bonding finger is expressed as:

$$Q=J_A=\frac{-Dab(C_L-C_0)}{L} \tag{14}$$

Then the diffusion concentration distribution of copper atoms is described in the PCB bonding finger (along the vertical direction), according to characteristics of steady-state diffusion expressed in Eqs. (15) and (16) :

$$J=\frac{\mathrm{d}m}{\mathrm{d}t}=-D\left(\frac{\mathrm{d}C}{\mathrm{d}Z}\right)=\text{Const.} \tag{15}$$

$$\mathrm{d}C=-\frac{J\mathrm{d}Z}{D} \tag{16}$$

Deducing from Eq. (14), we got:

$$J=-\frac{D(C_L-C_0)}{L}$$

so:

$$\mathrm{d}C=\frac{(C_L-C_0)}{L}\mathrm{d}Z \tag{17}$$

Each side of this equation is integrated, the concentration distribution of copper atoms is expressed as follows in the PCB bonding finger:

$$C(Z)=\frac{(C_L-C_0)}{L}Z+C_0 \tag{18}$$

3 Summary

The inherent driving force of copper atoms diffusion was described, the diffusion flux and concentration distribution expressions of copper atoms were drawn in the PCB bonding finger. Thus, it could be seen that concentration distribution was only relevant to the location of Z and copper atoms concentration of PCB bonding finger upper/under surface. Therefore, as long as the copper atoms concentration of upper/undersurface were known, distribution concentration of any point could be identified in the PCB bonding finger.

In the specific production practice of PCB bonding finger , in order to prevent copper atoms diffusion, the layer of nickel was firstly electroplated on the copper, then the gold, that was, nickel was used as a barrier layer of preventing copper atoms diffusion[12]. However, this method can only diminish the copper atoms diffusion, but not completely eliminate it. So the analysis of this article can be used as the theoretical basis of completely eliminating copper diffusion in the PCB bonding finger.

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