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Development of smoke corrosion and leakage current damage functions

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ABSTRACT

Smoke damage functions have been developed for representative materials used in smoke sensitive facilities such as semiconductor fabrication cleanrooms or data centers. Leakage currents and corrosion rates, normalized with the total smoke deposition per unit surface area, are presented from the flaming combustion of polycarbonate, PVC and Nylon. When coupled with smoke deposition rates, these damage functions can be used to assess expected damage levels for specific fire scenarios.

1. Introduction

Smoke is a mixture of (1) particulates consisting of soot, semi-volatile organic compounds (SVOC), and solid inorganic compounds; and (2) non-particulates consisting of very volatile organic compounds, volatile organic compounds, and liquid and gaseous inorganic compounds. Soot creates bridging between electrical conductors and conveys corrosive products, resulting in damage to electronics and electrical circuits through leakage current and corrosion, while SVOC and non-particulates stain and impart malodor to surfaces. Soot is also a very effective adsorbent and transport mechanism for SVOC, non-particulates and inorganic compounds. Facilities such as those associated with semiconductor fabrication or data storage and processing are particularly sensitive to smoke damage created through soot deposition leading to leakage current and/or corrosion.

1.1. *Leakage current*

Leakage current between two conducting elements occurs as a result of circuit bridging due to the presence of a conducting medium between the elements, such as water, conductive ions, soot, or dust. The increase of leakage current on electronic circuit boards can change overall circuit characteristics, e.g., degrade and/or damage circuit properties. This principle has been used to design a leakage current target for the measurement of smoke corrosivity [1–3]. The target, as shown in Fig. 1, has a comb-like pattern made of thin strips of copper with 40 insulating spaces between them. The dimensions of the target are shown in the figure.

Specifically, for example, with respect to the manufacture of semiconductors, leakage current is uncontrolled (“parasitic”) current flowing across region(s) of semiconductor structure/device in which no current should be flowing. Leakage is one of the main factors limiting increased computer processor performance. The presence of ionic compounds and soot in smoke deposited on the surface of a semiconductor is expected to damage the processor's functionality through an increase in leakage current.

1.2. *Corrosion*

Corrosion involves the reaction between a metal or alloy and its environment. It is an irreversible interfacial reaction, which causes the gradual deterioration of metal surface by moisture and corrosive chemicals. In aqueous or humid environments, corrosion is an electrochemical reaction in nature; it involves electron (e^-) transfer between anodic and cathodic reaction sites. For corroding metals, the anodic reaction is the oxidation of a metal to its ionic state [4].

1.2.1. *Anodic reaction*

$$M \Rightarrow M^{n+} + ne^- \quad (1)$$

Specific examples of anodic reactions:

$$Cu \Rightarrow Cu^{2+} + 2e^- \quad (2)$$

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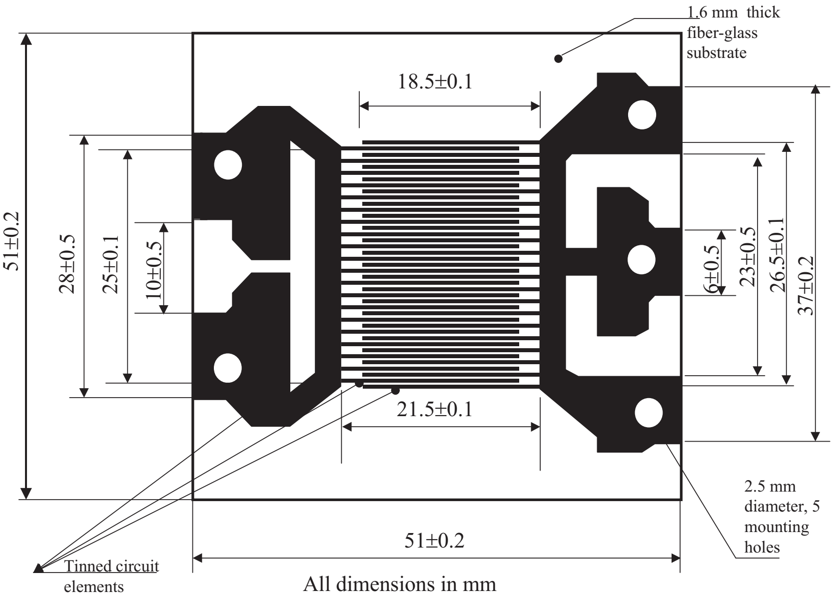

Fig. 1. Sketch of leakage current target (taken from Reference 2).

Table 1
Failure mechanisms and causes for electrical/mechanical equipment damage.

Failure mechanism	Failure cause
Corrosion	Metal contacts, cause open circuits
Shorts	Circuit bridging between contacts, cause leakage of current and shorts
Contact resistance	Coating of electrical contacts
Binding	Mechanical equipment (timers, hard disk drives, etc., impeded)

$$Al \Rightarrow Al^{3+} + 3e^{-} \quad (3)$$

$$Sn \Rightarrow Sn^{2+} + 2e^{-} \quad (4)$$

The cathodic reaction is a reduction process. For metallic corrosion, cathodic reactions like Eqs. (5)–(7) are frequently encountered. In acid solutions, hydrogen evolution and oxygen reduction reactions (Eqs. (5) and (6)) are the main cathodic reactions. In neutral or basic solutions, oxygen reduction reaction (Eq. (7)) is the primary cathodic reaction.

1.2.2. *Cathodic reactions*

Hydrogen evolution

$$2H^{+} + 2e^{-} \Rightarrow H_{2(g)} \quad (5)$$

Oxygen reduction (acid solutions)

$$O_2 + 4H^{+} + 4e^{-} \Rightarrow 2H_2O \quad (6)$$

Oxygen reduction (neutral or basic solutions)

$$O_2 + 2H_2O + 4e^{-} \Rightarrow 4OH^{-} \quad (7)$$

In general, corrosion caused by smoke is due to the presence of inorganic anions in smoke such as chloride (Cl^{-}), bromide (Br^{-}), and fluoride (F^{-}) plus moisture in the environment. In fires, corrosive combustion products such as HCl, HBr and HF are emitted along with the other combustion products, which are present as gases, liquids and solids. The corrosive combustion products are generally emitted as gases and liquids from inorganic anions in the structure.

The non-corrosive combustion gases and liquids are emitted as inorganic and organic compounds and water, whereas solids are emitted as soot and inorganic metals and dust. The solid combustion products are broadly defined as particulates and the gaseous and liquid combustion products are broadly defined as non-particulates. The mixture of particulates and non-particulates that include products with inorganic atoms is defined as smoke.

The main hazards regarding the exposure of electrical/mechanical equipment to smoke is the damage due to circuit bridging, corrosion, and binding, defined as smoke corrosivity. Circuit bridging occurs in reducing surface insulation and increasing leakage current for digital safety systems, multiplexers and functional circuit boards. In contrast, corrosion damage by acids and anions from smoke can be observed either short term or long term after the fire. Smoke contamination also leads to other types of electrochemical corrosion degradation of circuit boards, such as dendrite metal migration between conduction lines, localized corrosion of uncoated metal wires and contacting areas, etc. Failure mechanisms and causes for electrical/mechanical equipment as a result of exposure to smoke are listed in Table 1 [5].

2. Experimental set-up

The following section describes the experimental setup that has been developed for making various types of smoke damage and combustion process measurements. There are two main measurement stations within this setup. The first is the Smoke Exposure Chamber (SEC) and the second is the U-tube measurement duct. Smoke generated by the tube furnace supplies one of either of these measurement stations, but not both simultaneously. Fig. 2 shows the schematic of the Tube Furnace System experimental setup for (1) generating combustion products, (2) characterizing combustion products and (3) measuring various