Nanosensors for Electronics Packaging

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Abstract

Nanotechnology applications in the electronics packaging field are wide and varied, including the introduction of nanoparticle nanocomposites, carbon nanotubes, nanoparticle conductive inks and vias, and underfill fillers. Nanosensors comprise a major segment of the new nanotechnology developments, and there are opportunities to exploit some of these concepts and devices in electronics package diagnostics. This paper concentrates on two potential applications of one basic type of sensor structure (a metal nanodot array) to package diagnostics (corrosion detection) and research (strain monitoring.)

Introduction

A primary problem in modern packaging technology, e.g. flip-chip attachment, is thermomechanical stress, and resulting failure by loss of adhesion, solder fracture, etc. In other technologies, accumulated plastic strain in isotropic conductive adhesive joints, for example, may be the source of failure. In monitoring such effects, whether for research or *in situ*, the measurement is typically indirect, or requires bulky apparatus in a laboratory setting. There is a need for a small-scale, high gage factor sensor, which can be integrated on chip or board. Such a device could be useful in many locations on or within a package, even to detect pop-corning, for example.

Corrosion is another issue in many packaging applications, potentially wherever an interface between dissimilar metals is subject to humidity. The generic corrosion reaction releases hydrogen, and early onset of corrosion may be detected by a sufficiently sensitive detector of this byproduct.

The concept of a specialized chip which could monitor package parameters of interest was developed some years ago by Sandia Labs. However, the proposition here is to use nanoscale sensors which would take up negligible-on-chip real estate for production devices, even for many sensors distributed over many locations. (There may be need for on-chip sampling electronics, to provide a serial output to minimize I/O count overheads.

The discontinuous metal thin film (DMTF) is one of the simplest sensor structures possible. It consists of an array of metal nanodots which conducts current between two electrodes. The structure can be thought of as an array of multiple coulomb blocks, and indeed the simplest "array" of one island is a coulomb blockade device, (and could also function as a sensor.)

Discontinuous Metal Thin Films

DMTFs are readily formed in the early stages of nucleation and growth of noble or refractory metal films (Au, Ag, Pt, Pd, W, Mo,) on insulating substrates, by physical vapor deposition *in vacuo*, the key element being a weak atom-substrate interaction. DTFs consist of discrete metal islands, of dimensions in the 2-10nm range, separated by inter-island gaps of 2nm or more. These parameters can vary considerably, especially with substrate temperature. Significant electronic conduction is observed in DTFs [1, 2], but the lack of DMTF stability and reproducibility, which is the focus of current research, has been an impediment to successful commercial development.

Electronic conduction by electron tunneling between islands follows the form
$$\sigma = \sigma_0 \exp\text{-}\delta E/kT,$$
where the activation energy
$$\delta E = (q^2/4\pi\varepsilon)(r^{-1}\text{-}(r+s)^{-1})$$
is the electrostatic energy required to charge a small spherical island of radius, r, by removal of an electron to distance, s, (the inter-island separation,) in a medium of dielectric constant ε, with q the electronic charge, k Boltzmann's constant, T the absolute temperature, and $\sigma_0 = \lambda(4\pi m q^2/h^3 B)(\pi BkT/\sin\pi BkT)\exp\text{-}A\phi^{1/2}$ is the tunneling term, with $B = \frac{1}{2}A\phi^{1/2}$ and $A = 4\pi s(2m)^{1/2}/h$, where h is Planck's constant, and λ, m, and ϕ are the effective tunneling area, electronic mass, and tunneling barrier height.

Strain Gage

If the film is strained, the increase in gap widths, s, produces a significant increase in resistance, due to the exponential tunneling dependence. For a gage factor
$$\gamma = (dR/R)/(ds/s) = (4\pi/h)(2m^*\varphi)^{1/2}s,$$
order of magnitude calculation gives a gage factor around 50 for 2nm gaps, and in fact gage factors up to 200 are commonly observed. This model assumes only the tunneling gap contribution, and it has been shown that the activation energy term can have a significant impact too. Gage factors are enhanced by islands only weakly pinned to the substrate, as typically observed, but negative gage factors have also been observed.

Hydrogen Detector

A similar effect can be obtained for discontinuous Pd thin films in the presence of hydrogen. The Pd island swells, decreasing gap width, and increasing electron tunneling conduction [3-5]. There is an opposing surface effect, due to the increase of the Pd work function by hydrogen absorption, which is similar to the effect of other gases, so the islands must be designed to be large, with small gaps in order to maximize the unique Pd/H_2 effect. Example results, displaying both effects at different hydrogen concentrations/pressures, are shown below.
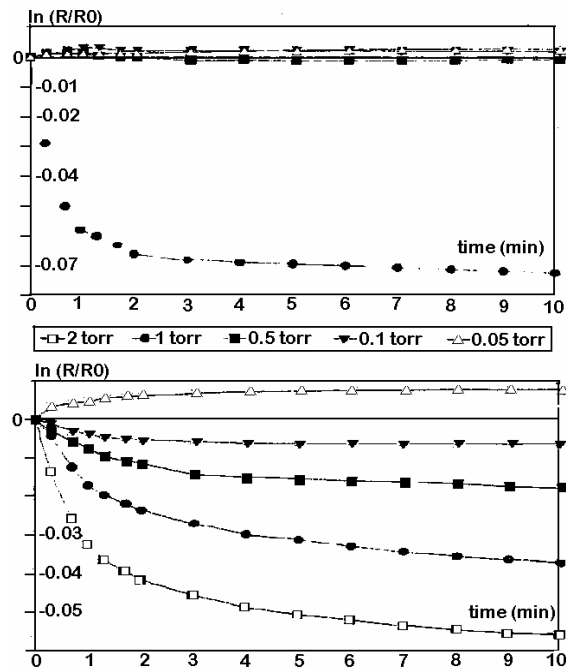
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