MATERIALS SCIENCE

Electronics Without Lead

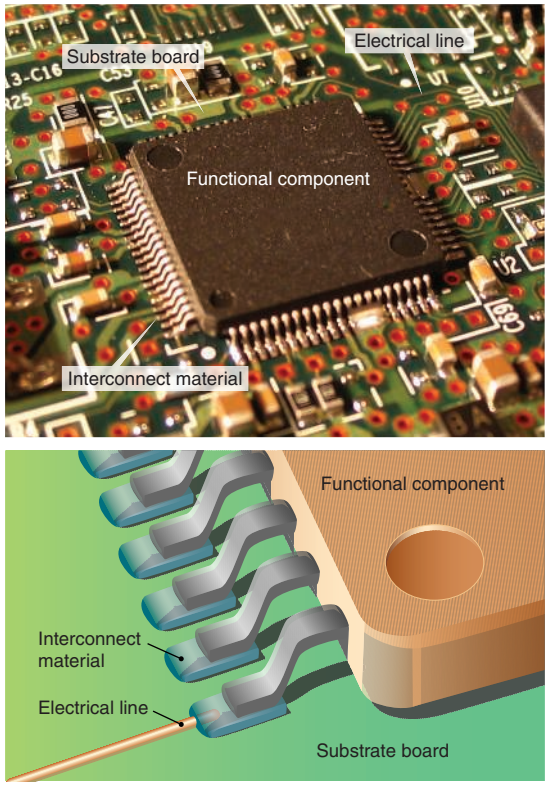
Yi Li, Kyoung-sik Moon, C. P. Wong

Tin-lead alloys are widely used as solder in the electronics industry (*1*, *2*). They serve as interconnects that provide the conductive path required to achieve connection from one circuit element to another (see the figure). In 2000, 10% of the lead consumed by U.S. industries was used to produce alloy solders for consumer electronics. Most of these products—such as cell phones and electronic toys—have a short service life, often ending up in a landfill within a few months or years. The disposed lead can leach into the drinking water, posing a severe health risk to humans. Attempts to recycle the lead in printed wiring boards of consumer electronic products have not been successful.

In response to concerns for the environment and human health, Japan required all new electronic products to be lead-free from January 2005; the European Union has introduced legislation to ban lead from electronic products by 1 July 2006. The U.S. government has not yet legislated against the use of lead in electronic products. In response to the new legislation, most major electronic manufacturers, including those in the United States, have stepped up their search for alternatives to lead-containing solders. To date, these efforts have focused on two alternatives: lead-free alloys and electrically conductive adhesives.

The most promising lead-free alloys contain tin as the primary element, because it melts at a relatively low temperature (232°C) and easily wets other metals. Depending on the application, different elements (such as silver, copper, bismuth, zinc, indium, and nickel) may be added (*3*–*5*). Among these alloys, tin/silver/copper alloys have been widely accepted as the most promising lead-free solders. A mixture of 95.4% tin, 3.1% silver, and 1.5% copper provides optimal strength, fatigue resistance, plasticity, and reliability.

However, the melting point of the latter alloy is 217°C; like most other lead-free alloys, this is more than 30°C higher than that of the tin-lead alloy with the lowest melting point (183°C). To obtain sufficient wetting by lead-free solders, the processing temperature during electronic assembly must therefore be raised by 30° to 40°C. This temperature increase reduces the integrity, reliability, and functionality of printed wiring boards, components, and other attachments (*6*). Preliminary research has shown that the use of metal nanoparticles may lower the melting temperature of lead-free solders (*7*–*9*). Even if the melting temperature can be lowered, several other important issues must be addressed, such as the implementation of a lead-free assembly process, the development of compatible lead-substrates, and the reliability of the lead-free solder joints.



Lead on the board. (Top) Photo of a functional component that is assembled on the board substrate via interconnects. **(Bottom)** Side view of the bonding between the component and the substrate via the interconnect material.

Electrically conductive adhesives are the other promising alternative to tin-lead solder. They consist of a polymeric resin (for example, an epoxy, silicone, or polyimide) that provides mechanical properties such as adhesion, mechanical strength, and impact strength and a metal filler that conducts electricity. Electrically conductive adhesives offer numerous advantages over conventional solder technology. They are environmentally friendly, require fewer processing steps (reducing processing cost), and allow a lower processing temperature (enabling the use of heat-sensitive and low-cost components and substrates) and smaller distances between the electrical lines in circuits (enabling the manufacture of smaller devices) (*10*).

Currently, there are many conductive adhesives on the market that are primarily targeted to low-power devices such as driver chips for liquid crystal displays. However, no commercially available conductive adhesive can replace tin-lead metal solders in all applications. Especially for high-power devices such as microprocessors, these polymer-based materials have critical drawbacks, including conductivity fatigue in reliability tests, limited current-carrying capability, and poor impact strength (*2*, *5*, *10*).

Recently, some progress has been made in elucidating the mechanisms underlying the conductivity fatigue and the limited current-carrying capability of conductive adhesives. Because galvanic corrosion is the main cause of conductivity fatigue, oxygen scavengers, corrosion inhibitors, and sacrificial additives (alloys with lower corrosion potential) have been used to stabilize the contact resistance and improve the reliability of conductive adhesives (*2*, *11*). To enhance the current-carrying capability of conductive adhesives, self-assembled monolayers with high current density were incorporated into the interface between metal fillers and substrates; the electrical conductivity and current-carrying capability of the resulting adhesives can compete with those of traditional solder joints (*12*).

Another critical property for electronic components is the ability to withstand impacts generated by, for example, dropping, strong vibration, or mechanical shock. Most microelectronic commercial conductive adhesives have poor impact strength. Thus, components that are assembled with conductive adhesives tend to sep-

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arate from the substrate upon being subjected to a sudden shock (*13*, *14*). The impact strength of conductive adhesives may be increased by decreasing the filler loading, using resins that absorb the impact energy generated by shock, and encapsulation of the surface-mounted devices (*15*).

Many challenges to producing lead-free interconnects remain to be addressed by scientists and engineers, but both lead-free solders and conductive adhesives show much promise. To make the two lead-free alternatives viable, conductive adhesives that can carry high currents and lead-free solders that have low processing temperature, high reliability, and good thermal mechanical properties are needed.

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CELL BIOLOGY

Prion Toxicity: All Sail and No Anchor

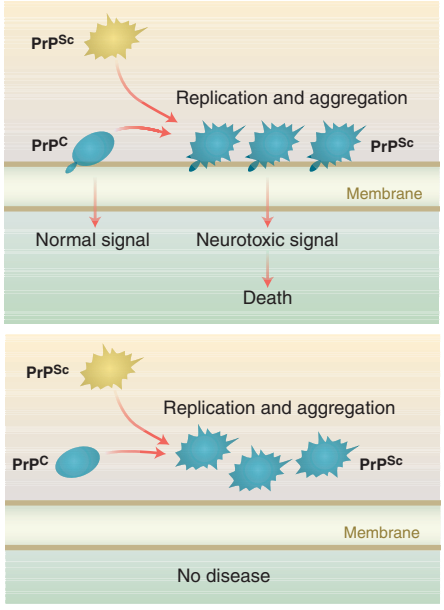
Adriano Aguzzi

Within the past 2 years, our understanding of the infectious particles responsible for fatal neurological conditions such as mad cow disease, scrapie, and Creutzfeld-Jakob disease has seen considerable progress (*1*). There is now strong evidence that prions, the culprit infectious particles, can be synthesized in systems that are completely free of cellular material (*2*, *3*). This may essentially settle the score as to the purely proteinaceous nature of the infectious agent. As to the march of prions toward the brain, or "neuroinvasion," a wealth of players has been uncovered, as well as an intricate relationship between immunological and nervous compartments of the host organism (*4*, *5*). Still, the physiological function of PrP^C, the form of prion protein that cells normally harbor, remains essentially mysterious. Also, we do not understand how the infectious form of the prion protein, a structurally distorted form of its normal counterpart, achieves brain damage. A tantalizing inroad has now been made by Chesebro and colleagues as to the latter question on page 1435 of this issue (*6*).

The causative agent of transmissible spongiform encephalopathies (TSEs) such as scrapie is PrP^{Sc}, a misfolded, protease-resistant version of the normal PrP^C protein (encoded by the *Prnp* locus in mice). PrP^{Sc} forms orderly aggregates that often progress into large extracellular deposits commonly described as brain plaques. It is argued that PrP^{Sc} multiplies by recruiting and converting PrP^C into further PrP^{Sc}. But this hypothesis does not explain how infectious prions proceed to induce the spongy brain lesions of TSEs and, eventually, extensive neuronal death. Curiously, PrP^{Sc} itself is innocuous: When the brain of a mouse lacking normal prion protein is grafted with brain tissue replete with PrP^C and then subsequently exposed to infectious prions, sizable amounts of PrP^{Sc} are produced, yet the mouse fails to develop TSE (*7*). So why aren't PrP^C-deficient neurons affected by the infectious agent?

Chesebro *et al.* have investigated this question in a sophisticated model system. During its early biogenesis, PrP^C is directed to the lumen of the endoplasmic reticulum, thus entering the cellular secretory pathway. A glycosylphosphatidylinositol (GPI) lipid anchor is then added to its C terminus, tethering the protein to the outer side of the cell membrane. Chesebro *et al.* redacted a *Prnp* transgene to remove the signal peptide responsible for GPI anchoring. As a consequence, the resulting GPI-negative transgenic mice expressed a monomeric, soluble secreted form of PrP^C.

When infected with PrP^{Sc}, the GPI-negative transgenic mice never developed clinical prion disease. Quite surprisingly, though, their brains were packed with PrP^{Sc} plaques! Evidently, removal of the GPI anchor abolished susceptibility to clinical disease while preserving the competence of the soluble PrP^C molecule to support prion replication. This interpretation fits very nicely with the growing body of evidence that normal prion protein may function as a signaling molecule, just like many other GPI-linked proteins. Altered PrP^C signaling may therefore be unhealthy (see the figure). Indeed, cross-linking of PrP^C on the surface of hippocampal neu-



Membrane anchoring is a crucial prerequisite for prion toxicity. (Top) Under normal circumstances, the cellular prion protein PrP^C is anchored to the cell membrane with a glycolipid moiety. Upon prion infection, PrP^C is converted into aggregates of a β-sheet conformer called PrP^{Sc}. This may affect signaling events involving normal, membrane-bound PrP^C, leading to neurotoxicity. **(Bottom)** Chesebro *et al.* (*6*) have generated transgenic mice expressing an anchorless, secreted version of PrP^C. When infected with prions, these mice never develop disease, although the secreted PrP^C is efficaciously transformed into PrP^{Sc}.

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