MinE stimulates the ATPase, releasing the proteins from the membrane. A challenge has been to understand how this dynamic interplay with the membrane is translated into a very orderly oscillation in the confines of the cell.

The simplicity of this system has attracted mathematical modelers seeking to determine the essential features necessary to produce the oscillation (*14*). Although none of the models are yet predictive and several variations exist, they suggest possibilities for the underlying mechanisms. A common basis for these models is that interactions between the proteins and the membrane prevent a uniform distribution—so-called dynamic instability. But questions have remained as to whether MinD and MinE are sufficient to generate the oscillations.

As a first attempt to recreate the oscillation, Loose *et al*. added fluorescently labeled MinD, MinE, and an energy source (ATP) to an enclosed system containing a lipid bilayer supported on a mica surface. An initial even distribution of the proteins on the bilayer evolved into waves of MinD and MinE moving across the surface. Each wave consisted of a wide band of MinD with a peak of MinE at the lagging edge of this band—MinE chewing away at the MinD with the released MinD regrouping at the leading edge of the band, resulting in a traveling wave. This wave is reminiscent of the oscillation in vivo where MinE chases MinD from midcell to one end of the cell (*15–17*).

The studies by Osawa *et al*. and Loose *et al*. show that two important components of bacterial cell division can self-organize once they are put into a container. So elegant and so simple. With the Z ring and the Min oscillation established in vitro, the next question is whether these systems can be combined to achieve spatial regulation.

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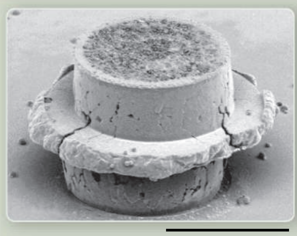
MATERIALS SCIENCE

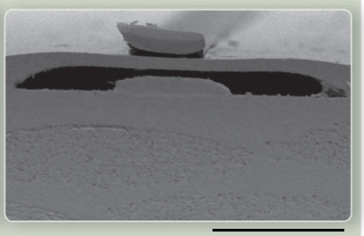
High-Frequency Chip Connections

Advanced interconnects will be required to keep pace with the increasing speed of future microelectronics.

Todd J. Spencer, Tyler Osborn, Paul A. Kohl

The bandwidth needs for future electronic systems are expected to expand in the next decade because of the large data requirements of multimedia and high-performance computing systems. With the frequency of high-speed input-output (I/O) connections expected to increase from the 2 GHz currently available to more than 67 GHz (*1*), this will require not only fast and reliable processors, but equally fast and reliable data links between system components and the network. We discuss some of the advances that have been achieved and the challenges that lie ahead for high-performance interconnects.





Better interconnects. (**Left**) Two copper pillars joined through an electroless fusion process. (**Right**) Cross section of air-isolated microstrip line.

High-speed communication between microprocessors and other chips or networks depends on both electrical and optical links. Optical links are particularly beneficial over long distances (tens of meters to several kilometers) because of the low loss in optical fibers. Multiple data sets can be transmitted through the same fiber, providing higher data rates than those achievable electrically. Signal-processing techniques can also improve data rates but have disadvantages in circuit complexity and power dissipation. Optical interconnects also perform well at short distances (tens of micrometers to meters) (*2*), but integration is difficult because of the requirements of precise alignment and losses at 90° routing angles. Optical sources and receivers must also be maintained at prescribed temperatures to prevent changes in operating characteristics (such as wavelength and current) that can render the device inoperable.

Electrical connections alleviate many integration challenges in high-performance computing systems but require improvements to reduce the signal loss. An electrical signal falls off exponentially, with a decay constant γ, along the length of a transmission line. This signal decay arises from electrostatic (i.e., capacitive) and magnetic (i.e., inductive) contributions from the circuitry. To achieve low loss, the lines must have insulators that provide low capacitance and inductance. The lines must also be insulated from neighboring lines to prevent cross-talk and undesirable capacitive coupling and inductance that contribute to noise in the circuit.

For more than a decade, the first-level connection between a high-performance chip and the external circuitry has typically been made via solder ball connections between the chip and an epoxy-fiberglass substrate. However, solder has many restrictions as the interconnect size continues to shrink. The formation of brittle copper-tin intermetallics can compromise thermomechanical reliability. Solder also has low electromigration resistance, which becomes important as the diameter of interconnects is reduced and current density

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increases. Solder connections are limited to spheres with an aspect ratio of 1:1 (height:diameter), making connections with high aspect ratios (large chip-to-substrate stand-off distances) very difficult to fabricate. This causes difficulties with flow in the placement of underfill (a stress-distributing layer around the solder balls). Fragile on-chip interlayer dielectrics require lower-stress I/O so as not to cause fracture.

The next frontier is an all-copper chip-to-substrate interconnect, which would eliminate many of the problems with solder. Copper has superior electrical properties relative to solder with respect to both electrical conductivity and electromigration resistance. It also has superior mechanical properties, such as yield stress and elastic modulus, that allow for the design of mechanically compliant interconnect structures. Having no tin-based materials present eliminates the formation of brittle intermetallics, thus leading to an improvement in the thermomechanical reliability of the device. Finally, copper interconnects are capable of forming high aspect ratios because they are not melt-cast and therefore don't need to be spherical in shape. This will pave the way for fine-pitch interconnects with higher stand-off distances and complex shapes, such as shielded coaxial structures, which can support high-frequency I/O. Copper-to-copper bonding via methods that are compatible with temperature-sensitive substrate materials has been reported using surface-activated bonding (*3*) and electroless deposition and annealing (*4*). The left panel of the figure shows two (short) copper pillars joined by the all-copper electroless process. Such copper bonding facilitates connections for low-loss high-frequency operation that is not possible with solder.

Substrate and board-level signaling are particularly challenging because of the longer wires that require small γ to maintain adequate voltages. Conventional board-level wires, etched copper traces on fiberglass and epoxy substrates, suffer from large losses due to substrate capacitance and conductance. Improved performance can be achieved with more expensive ceramic substrates that offer comparable capacitance loss while reducing dielectric conductance. Such ceramics offer mechanical benefits due to the lower coefficient of thermal expansion.

Substrate capacitance can be reduced through the use of polymer dielectrics, although this typically is associated with an increase in substrate conductance. Further reduction of the coupling capacitances and conductances can be achieved by incorporating gaseous cavities in the material, via either a porous matrix or a continuous air cavity supported by a dielectric (*5*). At higher frequencies, such nonhomogeneous dielectric layers are undesirable, as propagation at different velocities through different media leads to distortion of the electric field. Copper surface roughness can also degrade performance at high frequencies because of the longer path length along the surface, where charge concentrates at higher frequencies as a result of the skin effect. Surface undulations due to glass fibers in epoxy-fiberglass substrates pose challenges to both electrical and optical systems (*6*).

System-level integration of air-insulated copper lines will remain difficult until a variety of mechanical, thermal, and electrical considerations are addressed. Mechanical integrity of copper lines is important to maintain reliability and prevent failure due to stress and electromigration (*7*). Inclusion of air insulation thus poses a particular challenge, as the lack of confining stress allows copper surface diffusion to proceed with greater ease (*8*). The right panel in the figure shows a microstrip copper signal line on a substrate with its return path separated by an air-polymer gap. Moisture absorption into air cavities is particularly troublesome because it can increase the capacitance and conductance, which may result in short circuits. Air-insulated circuits will require surface treatments or hermetic sealing to circumvent these challenges. Maximized electrical performance ultimately corresponds to minimized thermal performance, as air is also an ideal thermal insulator. This increase in thermal resistance may limit heat removal from the package and prevent further improvements in system performance.

Any advances in integrated circuit performance will need to be matched by performance enhancements at the package level. Work is under way toward providing cost-effective high-speed chip-to-chip communication.

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BIOGEOCHEMISTRY

News About Nitrogen

M. Claire Horner-Devine[1] and Adam C. Martiny[2]

Discoveries of microbial pathways, players, and population dynamics challenge conventional models of the nitrogen cycle.

Understanding of microbial diversity and interactions is crucial for quantifying fluxes in nutrient cycles and forecasting ecosystem responses to global environmental changes. This is particularly true for the nitrogen cycle. In contrast to the carbon cycle, none of the steps in the nitrogen cycle can be measured at a global scale on the basis of satellite data. Instead, global biogeochemical models rely on field measurements of nitrogen concentrations and fluxes, combined with rate constants from a few known organisms, to balance the net flux of nitrogen.

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Thus, incomplete knowledge of microbial diversity and ecological dynamics may mislead estimates of fluxes in the nitrogen cycle.

Three discoveries illustrate how much scientists are still learning about the nitrogen cycle. First, ammonia oxidation by microbes was thought to proceed only in the presence of oxygen. However, bacteria have been shown to be capable of oxidizing ammonium anaerobically, using nitrite rather than oxygen as the electron acceptor, resulting in the production of N_2 gas (*1*). Although this "anammox" reaction was theoretically predicted, finding anammox organisms has helped to explain deviations between models of the marine nitrogen cycle and observed ammonia concentrations and N_2 production in anaerobic marine environments (*2*).

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