higher doping density to be used in the channel while maintaining a low resistance when the transistor is switched into the conducting state. This increase in the channel doping density increases the channel barrier, thereby improving the isolation between source and drain when the transistor is turned off. This permits the lateral distance between the source and drain regions to be scaled. Thus, decreased capacitive coupling and inability to scale lateral dimensions may result if oxide thickness cannot be scaled.

Statistical fluctuation is also a potentially fundamental limit for continued transistor scaling (*6*). The transistor dimensions have become so small that the number of dopant atoms that control the electrical characteristics is on the order of a hundred. As a result, small changes in the exact number and distribution of the atoms can cause appreciable changes in the device behavior. The statistical nature of the dopant distribution is inherent to the fabrication process and cannot easily be changed. For very large integrated circuits that can use more than 10 million transistors, this statistical variation can cause serious design problems. Unless ways for reducing statistical variation are found, it may not be possible to scale dimensions to the point where tens of atoms determine the device characteristics.

Solutions for these problems have not yet been found (*7*). It has been proposed that the semiconductor material must be changed to continue transistor scaling. Alternate semiconductor materials such as GaAs and SiGe have been evaluated for more than 20 years, but although these materials have found a niche for certain applications, neither has been able to solve the problems of silicon without causing even more complex problems. Alternate insulating materials for the gate dielectric are also under evaluation. By using an insulating material with a dielectric constant much larger than that of SiO_2, the thickness of the material can be increased while still increasing the capacitive coupling. The increase in thickness would strongly decrease the electron tunneling current and would permit continued scaling of the transistor. Unfortunately, no material with a substantially increased dielectric constant that is also compatible with MOS transistors has yet been found.

A substantial effort is being made to increase charge concentrations by creating metastable states that are far from thermodynamic equilibrium. Processes such as laser annealing and epitaxial growth have been proposed for creating ultrahigh mobile charge concentrations. Unfortunately, these carrier densities are fragile, and the metastable states are extremely difficult to maintain during processing of the device.

These fundamental issues have not previously limited the scaling of transistors and represent a considerable challenge for the semiconductor industry. There are currently no known solutions to these problems. To continue the performance trends of the past 20 years and maintain Moore's law of improvement will be the most difficult challenge the semiconductor industry has ever faced.

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PERSPECTIVES: POLYMER CHEMISTRY

Nanoscale Polymerization Reactors for Polymer Fibers

Petri Lehmus and Bernhard Rieger

The synthesis of a high-performance polymer from inexpensive starting materials usually requires sophisticated polymerization catalysts and postprocessing steps to control the product's morphology and hence its macroscopic properties. Alternatively, expensive monomers can be used to impose morphological order; for example, this is how the bullet-proof Kevlar is made by DuPont. On page 2113 of this issue (*1*), Kageyama *et al.* introduce a "microprocessing" method that may make it easier to achieve high control over polymers made from simple starting materials.

Kageyama *et al.* use a titanocene catalyst supported within the pores of a mesoporous silica for the in situ production of polyethylene with a novel fibrous morphology. The nascent polymer chains cannot fold within the narrow reaction channels of the honeycomb-like support and therefore grow out of the porous framework before they assemble, resulting in the formation of extended-chain crystalline fibers (see bottom panel in the figure). By using regularly arranged nanoscopic, one-dimensional polymerization reactors, the authors thus achieve oriented growth of polyethylene macromolecules that normally requires postprocessing steps.

Earlier reports on mesoporous catalyst systems containing high concentrations of accessible and structurally well-defined active sites indicated their potential for controlling olefin polymerization reactions (*2*, *3*). These investigations also gave first indications of the influence of such catalysts on polymer morphology. Kageyama *et al.*—who coined the term "extrusion polymerization" for their fascinating concept of oriented nanoreactors—demonstrate that conceptually new material properties can result from combining the rational design of organometallic catalysts with nanotechnology.

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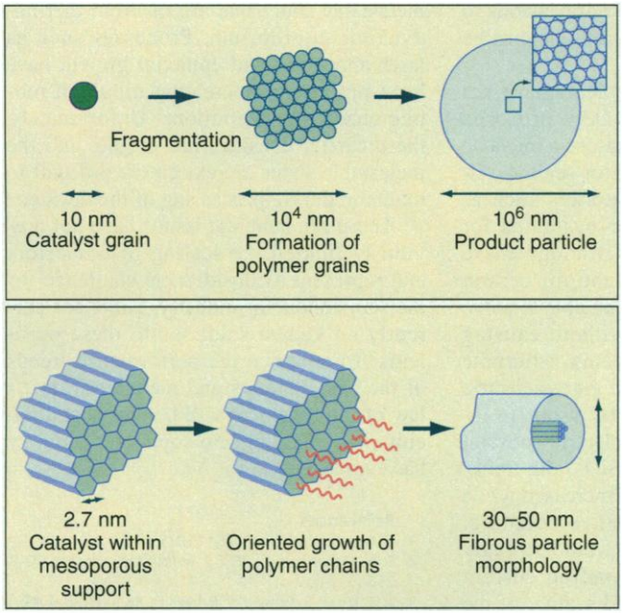
The application of porous catalyst supports as microreactors is well-established in industrial processes with fourth-generation Ziegler-Natta catalysts (*4*, *5*). Excellent polymer particle morphology control is achieved by the granule technology, brought to perfection in the Spheripol process of Himont in Italy. In this process, polymerization inside porous catalyst grains results in fragmentation of the grains and formation of spherical polymer granules (see top panel in the figure). An immense improvement of the material strength can be achieved by orienting the crystalline phase of the polyolefin, but this requires expensive postprocessing steps. Bidirectionally extended polyolefin films and ultratough polyethylene fibers, such as Dyneema (which is produced and commercialized by DSM), are examples of oriented, high–molecular weight materials that have tensile strengths up to two orders of magnitude higher than those of standard high-density polyethylene products.

The conventional $TiCl_3$-based Ziegler-Natta catalysts used in the processes described above suffer from structural inhomogeneity of the different reaction centers, resulting in products with broad molecular weight and uneven comonomer distributions. Olefin comonomers are used to alter the crystallinity of the polyolefins to control their properties. This is



Directed growth. The particle growth process in traditional Ziegler-Natta polymerization (**top**) is compared with the concept of oriented nanoreactors of Kageyama *et al.* (*1*) (**bottom**).

best achieved with catalysts that generate a statistical comonomer distribution. For instance, metallocene dichlorides are organometallic complexes with a uniform chemical structure of each active site (*6*, *7*) which ensures high precision of the polymerization reaction, resulting in a narrow molecular weight distribution, an even comonomer distribution, and high stereoregularity of the polyolefin products. Metallocene-based polymer catalysts are now conquering the polyolefin market. Intensive research on homogeneous metallocene catalysts has led to a genuine understanding of the elementary steps of the coordination polymerization mechanism and precise correlations between catalyst symmetry and the resulting polymer microstructure (*6*–*9*).

The discovery of mesoporous MCM-41 silicas in 1992 (*10*) has opened a route to a completely new generation of polymerization catalysts, which combine the advantages of tunable, molecular, defined metallocene catalysts and extended nanoreactors. In these systems, metal complexes have to be attached to the inner walls of the high–surface area solids. Kageyama *et al.* demonstrate a case in which this challenge has been met with success. Standard, spherical silica gels are already used as support materials for the youngest generation of Ziegler-Natta catalysts, and it may be expected that the new, linear silica nanoreactors will find their way into industrial application. The economic balance between polymer properties and catalyst productivity will be decisive. The ongoing development of coordination catalysts also comprises late transition metal complexes, which will extend the set of conventional and easily available monomers to polar building blocks.

We can envision a highly sophisticated construction kit, in which the proper choice of monomers, catalysts, and nanoreactors will lead to a portfolio of new organic materials with precisely controlled properties. The design of novel polymer architectures from conventional monomers has only just begun.

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PERSPECTIVES: CELL BIOLOGY

All Creatures Great and Small

Sally J. Leevers

Understanding how animals grow (increase in mass) at a certain rate and achieve a specific final size is a challenge that has long fascinated biologists (*1*). The rate of growth and the final size of an organism result from changes in the size and number of cells during development. Early clues to the process of growth regulation were provided by the identification of mutations in yeast that blocked cell division but not cell growth. This simple observation implied that growth can continue in the absence of cell division, and therefore that growth is not simply a matter of increasing cell number. Surprisingly, although these experiments provoked much research into the regulation of cell division, less attention has been paid to the regulation of cell growth (increase in cell size) and of overall growth (increase in mass) in multicellular organisms. However, recent work in the fruit fly *Drosophila* has confirmed that, here too, growth can occur without cell division and that inducing cell division does not necessarily promote growth (*2*, *3*). How then is growth regulated?

On page 2126 of this issue, Montagne and colleagues identify a signaling molecule, *Drosophila* S6 kinase (DS6K), which, when mutated, slows growth and reduces cell size and body size (*4*). In mammals, S6 kinases (also called p70 S6 kinases) are targets of insulin signaling that regulate the synthesis of proteins encoded by 5′TOP (terminal oligopyrimidine tract) mRNAs (which are primarily components of the translation machinery). Recently, other molecules on the insulin signaling pathway (*5*–*8*) and other molecules involved in protein synthesis (*9*) have also been shown to regulate growth rate and/or cell size and body size in *Drosophila*. Taken together, these genetic studies in the fruit fly identify a signaling pathway and a biosynthetic process that contribute directly to the regulation of growth during development.

Montagne and colleagues set out to examine the function of DS6K by identifying *Drosophila* strains with null mutations in the *ds6k* gene. They found that flies without DS6K were developmentally delayed (that is, they grew at a reduced rate) and that their final size was approximately half that of wild-type flies (*4*). Inspection of the wings of these small creatures revealed that they were made up of cells that were reduced in size but similar in number to those of wild-type flies. To find out what was happening earlier in development, the authors examined the larval imaginal discs, sacks of epithelial cells that reorganize during metamorphosis into adult epidermal organs such as the wing. They found that

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[1] **Extrusion Polymerization: Catalyzed Synthesis of Crystalline Linear Polyethylene Nanofibers Within a Mesoporous Silica**

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