abrogation of epidermal growth factor signaling reduces, but does not eliminate, activation of ERK1/2 (*3*) implicating targets elsewhere, including factors upstream of epidermal growth factor expression. Moreover, luteinizing hormone may activate steroidogenesis by interacting with ERK signaling pathways (*8*). Disruption of this interaction could account for the dysfunctional steroidogenesis observed in ERK1/2-deficient mice. Autocrine regulation of the late stages of follicle maturation is mediated by estrogens, produced by granulosa cells, which act through membrane-type estrogen receptors at the cell surface and activate ERK1/2 (*9*). Although this receptor alone cannot support ovulation (*10*), it may be that the ERK1/2 signal is essential for this process.

The phenotype of the ERK1/2-deficient mice is similar to that seen in mice engineered to lack the transcription factor CCAAT/Enhancer-binding protein–β (C/EBPβ), suggesting that C/EBPβ is a major downstream effector of ERK signaling pathways. Additional potential targets were not explored, but candidates include the receptor-interacting protein 140 (Rip140), because this factor is a phosphorylation target of ERK2 (*11*) and mice lacking this factor cannot ovulate (*12*). ERK signals are not only induced by a number of extracellular stimuli but they are frequently pleiotropic. The absence of ERK1 and ERK2 in granulosa cells not only disrupted the action of epidermal growth factor-like molecules, but other ERK-generating systems are probably impaired as well as targets beyond C/EBPβ-mediated transcription. The findings of Fan *et al.* should help elucidate ovarian pathology such as polycystic ovarian disease, a common condition in which ERK1/2 activation is attenuated in follicle cells (*13*), and other anovulatory and infertility-producing conditions in humans.

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APPLIED PHYSICS

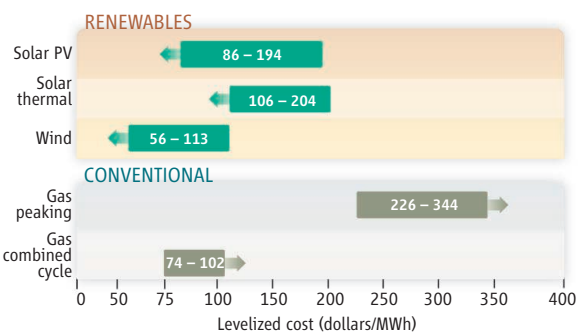
Photovoltaics Power Up

The power-generating capacity of solar cells, while currently small relative to other sources, is increasing exponentially.

Richard M. Swanson

The global photovoltaic (PV) power industry is experiencing dramatic technology advances and market growth. Over the past 20 years, manufacturing output has grown by a factor of 200, reaching 5 gigawatts (GW) in 2008. The total accumulated installed capacity is now around 15 GW. This is quite small relative to the world's 4000 GW of installed electric generation capacity—just 0.375% to be precise. However, industry leaders expect similar rapid growth over the coming years, with PV generation a major contributor to power generation 20 years hence (*1*).

In this quickly evolving environment, investors must assess which technologies and companies are best positioned, policy-makers must assess what role PV generation should play in our energy mix, utility planners must assess the impacts this will have on the electric grid, government and industry must decide how to allocate research and development (R&D) funds, and citizens must sort through a barrage of conflicting messages. For example, a recent *Wall Street Journal* opinion editorial article states, "There's an unavoidable problem with renewable-energy technologies: From an economic standpoint, they're big losers" (*2*). Perhaps this was once true when the industry was so small that it didn't matter anyway.



Measuring up. Levelized cost of energy by resource for new generation constructed in the 2009 to 2012 time frame. Prices include the 30% U.S. federal investment tax credit for renewables. PV is a viable utility option, with its competitiveness only expected to increase as PV costs decrease and gas prices rise. [Source: Lazard Capital Markets, 1/9/09]

But in many cases it is no longer true today.

Driven by advances in technology and increases in manufacturing scale and sophistication, the cost of PV has declined at a steady rate since the first solar cells were manufactured (*3*). For example, in 2000, solar cells typically used 15 g of expensive, highly refined silicon to generate 1 W of power. By comparison, SunPower Corporation's modules currently use only 5.6 g/W. Today, the manufacturing cost of standard crystalline silicon modules produced in a state-of-the-art facility is around $1.40/W (*4*). This cost includes the cost of refining silicon but not the added gross margin in sales price. Manufacturers foresee manufacturing cost to fall to $1/W within 5 years. An upshot of these cost reductions is that the levelized cost of energy (LCOE) for PV plants (see the figure) is now in the range of conventional generation options when taking into account the impact of the U.S. federal 30% investment tax credit, and will be fully competitive without that incentive in 5 years. Perhaps surprisingly, PV electricity today costs less than that from a new natural gas peaking plant, and is rapidly encroaching on combined cycle baseload generation costs.

From the perspective of an electric utility, what counts in making new generation decisions is the cost of electricity from the new plant. That their customers might pay a lower cost due to older, lower-cost generation in the mix (such as from hydroelectric or coal plants) is irrelevant when more capacity is needed. This fact has contributed to the recent increase in interest in PV on the part of electric utilities. For example, the California utility Pacific Gas and Electric (PG&E) has recently contracted for the purchase of 800 MW of PV-generated power (*5*). When utilities consider adding PV, they take into account not only its cost effectiveness but also its lack of fuel price risk, lack of potential carbon emission costs, minimal

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siting limitations, and lack of water use. Furthermore, construction times are short; for example, the PV industry installed more than 2 GW of PV power plants in Spain during 2008. Construction times for 2 GW of conventional generation would be 10 to 15 years. PV will thus not be insignificant much longer.

Conventional crystalline silicon modules compete with emerging thin-film technologies. Leading thin-film producers have lower cost, but at lower module energy conversion efficiency. The lower efficiency results in higher installation cost, with the result that there is near cost parity at the installed-system level. Indeed, there is a spectrum of technologies—from higher-performance, higher-cost modules to lower-performance, roll-on thin films—all competing successfully. Crystalline silicon modules are capable of attaining the long-term cost targets. Therefore, one should not think of thin-film technologies as somehow disruptive or uniquely enabling for the emergence of large-scale PV. Thin films are rather new technologies that may, if successful, help drive costs lower over time. The competition from crystalline silicon, however, will remain formidable because of the vast R&D resources being deployed. New entrants to the PV industry need to be cognizant of this fact as they allocate their own capital to the field.

Our energy future is becoming clearer. PV will not be a panacea, but it will take its place as a major source of energy alongside energy efficiency, other renewables, nuclear, and improved conventional generation, perhaps with carbon sequestration, as we transition to a carbon-free electric grid over the next half century.

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APPLIED PHYSICS

Two Beams Squeeze Feature Sizes in Optical Lithography

Competing activation and deactivation effects with shaped light beams could create in integrated circuit features much smaller than the beams' wavelengths.

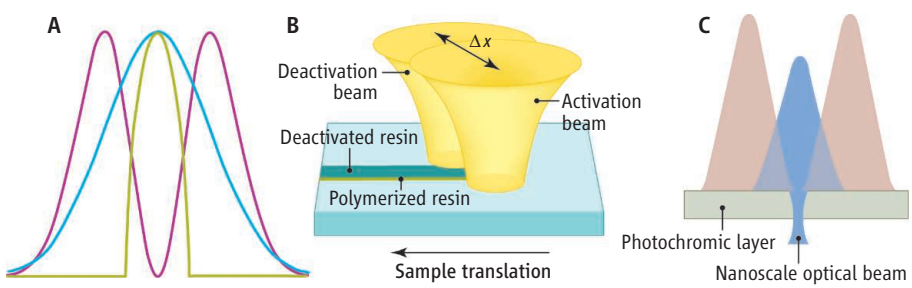
Joseph W. Perry

The fabrication of electronic circuits on chips relies on the patterning of surfaces by optical lithography, which is used to control where different components—metal wires, semiconductor gates, and oxide insulators—form (*1*). Three papers in this issue (*2*–*4*) report a new approach to optical lithography that allows small feature sizes to be created more easily than with traditional approaches.

In optical lithography, a light-sensitive film, called a photoresist, is exposed in selected areas by using a patterned mask. The light triggers chemical reactions that change the film's solubility. Solvents are then used to remove the exposed or unexposed areas, so that only selected areas on the chip undergo the next processing step. For example, after selective removal of photoresist, protected parts of a semiconductor layer become separated gate regions, whereas exposed regions are open for doping or deposition of electrodes.

Feature sizes as small as 45 nm can now be achieved in device fabrication, beating the diffraction limit set by the wavelength of the far-ultraviolet (FUV) light used for exposure (193 nm) through clever optical tricks (*5*). However, the light sources and the masks that create the patterns are costly; even higher costs can be anticipated for the shorter wavelengths needed for even smaller feature sizes. A simpler and less costly way to achieve smaller features is to use light to control the kinetics of the reactions that occur within the film. The three studies in this issue [Scott *et al.* (*2*), page 913; Li *et al.* (*3*), page 910; and Andrew *et al.* (*4*), page 917] make use of comparatively longer-wavelength light (UV to near infrared) that beats diffraction limits in optical lithography and creates features on the scale of tens of nanometers. In these approaches, one optical beam controls the spatial distribution of exposure while another beam induces chemical activation.

The classical resolution limit imposed by diffraction (about half the wavelength of light) applies to any light source focused by a lens. When coherent laser sources are used, destructive interference effects can restrict the actual area being illuminated through a mask. In this way, quarter-wavelength (45 nm) features can be created with 193-nm light from an argon fluoride excimer laser with phase-shift masks.



Two beams create smaller features. (A and **B)** The polymerization reactions initiated by a beam of light exciting a photoresist, which changes its solubility, can be inhibited by a second light source. (A) In the exposure scheme used by Scott *et al.*, the second coincident beam (whose profile is shown in purple) surrounds the first beam (shown in blue), which has a different wavelength and activates a reaction inhibitor. The net activation profile is shown in green. (B) In the work of Li *et al.*, an intense initiator beam is followed by a second, longer-duration beam of the same wavelength that inhibits the reaction. The beams can be coincident or offset, as shown by a distance Δx. (C) Two light sources can be used to create grating lines much smaller than the wavelength of either source. Andrew *et al.* place a photochromic film over the photoresist. A grating of UV light (325 nm, shown in blue), which makes the film transparent, is offset from a grating created by red light (633 nm) that makes the film opaque. The UV light penetrates a nanoscale region as small as ~40 nm, which is much smaller than its wavelength.

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