against the metal surface, after which the sample is annealed at 900–950°C. The researchers observed negligible ethylene adsorption or decomposition when the same process was followed but without the ion gun treatment.

The researchers obtained monolayers of high-quality graphene on Cu(111) substrates and atomically characterized them in UHV using scanning tunneling microscopy (STM). As expected for graphene monolayers weakly coupled to substrates, several moiré patterns with different periodicities were observed due to small rotations of the graphene lattice with respect to the substrate. As shown in the figure, relatively large defect-free regions of graphene monolayer were grown on the Au(111) surface. These findings were supported by low-energy electron diffraction measurements and Auger spectroscopy and confirmed the macroscopic formation of graphene on the Au(111) surface.

The properties of the graphene/ metal contact were also investigated and were shown to be weaker than in any previously reported graphene/metal system. The Fermi wave vector, estimated from low-bias STM images, where standing waves coming from the Au(111) surface are observed through the graphene layer, is in perfect agreement with the value for pristine Au(111). The minimum around the Fermi level observed in differential conductance plots, as obtained with STM, is associated with the Dirac point of the graphene's electronic structure—an indication of the lack of doping for this system. The researchers said, "Our new method paves the way to extend the range of possible substrates for the epitaxial growth of graphene to other low reactivity metals."

**Steven Trohalaki**

**Energy Focus**

## Electronic bucket brigade could boost solar-cell voltages

If solar cells could generate higher voltages when sunlight falls on them, they would produce electrical power more efficiently than is currently possible. Now a team of researchers at Lawrence Berkeley National Laboratory (Berkeley Lab) and the University of California–Berkeley (UCB) has studied bismuth ferrite, or BFO, to determine how the photovoltaic process occurs in materials known as ferroelectrics, known for developing very high voltages under illumination. The researchers reported their findings in the September 16 issue of *Physical Review Letters* (DOI: 10.1103/PhysRevLett.107.126805).

"We worked with very thin films of bismuth ferrite, or BFO, grown in the laboratory of our colleague Ramamoorthy Ramesh," said Joel Ager of Berkeley Lab's Materials Sciences Division (MSD), who led the research effort. "These thin films have regions—called domains—where the electrical polarization points in different directions. Ramesh's group is able to make film with exquisite control over this domain structure."

Because BFO has a range of unusual properties, the group led by Ramesh, who is a member of MSD and a professor of materials sciences, engineering, and physics at UCB, has long studied its characteristics by building custom devices made from the material.

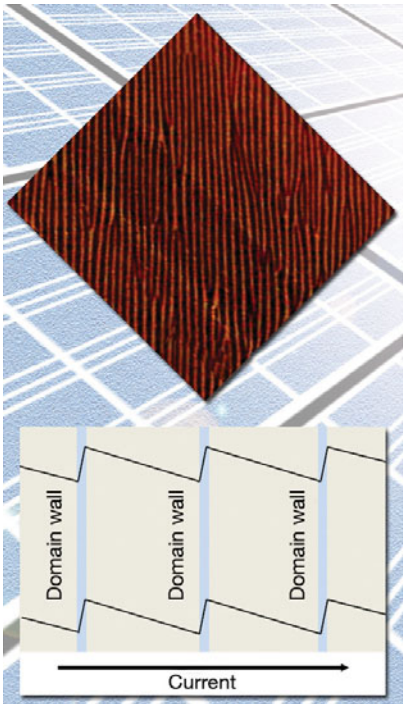
The BFO films studied by Ager and his colleagues have a unique periodic domain pattern extending over distances of hundreds of micrometers. The domains form in stripes, each measuring 50–300 nm across, separated by domain walls 2 nm thick. In each of these stripes the electrical polarization is opposite from that of its neighbors.

Because of the wide extent and highly periodic domain structure of the BFO thin films, the research team avoided the problems faced by groups who had tried to understand photovoltaic effects in other ferroelectrics, whose differences in polarity were thought to surround impurity atoms or to occur in different grains of a polycrystalline material.

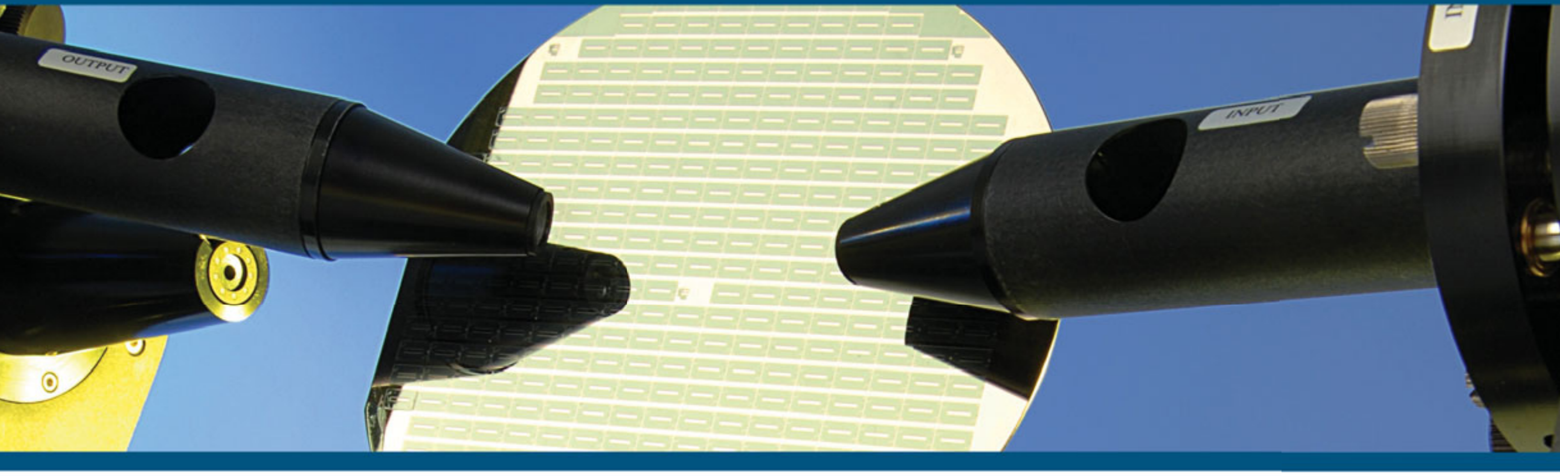
By contrast, said Ager, "We knew very precisely the location and the magnitude of the built-in electric fields in BFO." Thus Ager and J. Seidel of MSD were able to gain "full microscopic understanding" of what went on within each separate domain, and across many domains.

"When we illuminated the BFO thin films, we got very large voltages, many times the bandgap voltage of the material itself," said Ager. "The incoming photons excite the electrons and create corresponding holes, and a current begins to flow perpendicular to the domain walls—even though there's no junction, as there would be in a solar cell with negatively and positively doped semiconductors."

In an open circuit the current flows at right angles to the domain walls, and to



At top, domains with opposite electrical polarization, averaging about 140 nm wide and separated by walls 2 nm thick, form a well-aligned array in a thin film of bismuth ferrite. When illuminated, electrons collect on one side of the walls and holes on the other, driving the current at right angles to the walls. Voltage increases as excess electrons accumulate stepwise from domain to domain.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measure it the researchers attached platinum electrical contacts to the BFO film. Ager said, "The farther apart the contacts, the more domain walls the current had to cross, and the higher the voltage."

It was clear that the domain walls between the regions of opposite electrical polarization were playing a key role in the increasing voltage. These experimental observations turned out to be the clue to constructing a detailed charge-transport model of BFO, a job undertaken by J. Wu of MSD and UCB, and UCB graduate student D. Fu.

The model presented a surprising and simple picture of how each of the oppositely oriented domains creates excess charge and then passes it along to its neighbor. The opposite charges on each side of the domain wall create an electric field that drives the charge carriers apart. On one side of the wall, electrons accumulate and holes are repelled. On the other side of the wall, holes accumulate and electrons are repelled.

While a solar cell loses efficiency if electrons and holes immediately recombine, that cannot happen here because of the strong fields at the domain walls created by the oppositely polarized charges of the domains.

"Still, electrons and holes need each other," said Ager, "so they go in search of one another." Holes and electrons move away from the domain walls in opposite directions, toward the center of the domain where the field is weaker. Because there is an excess of electrons over holes, the extra electrons are pumped from one domain to the next—all in the same direction, as determined by the overall current.

"It's like a bucket brigade, with each bucket of electrons passed from domain to domain," Ager said, who describes the stepwise voltage increases as "a sawtooth potential. As the charge contributions from each domain add up, the voltage increases dramatically."

BFO itself is not a good candidate for a solar-cell material—for one thing, it responds only to blue and near ultraviolet light, which eliminates most of the solar spectrum. "So we need something that absorbs more light," said Ager.

The efficiency of BFO's response to light—the ratio of charge carriers per incoming photons—is best near the domain walls. While very high voltages can be produced, the other necessary element of a powerful solar-cell, high current, is lacking.

Nevertheless, said Ager, "We are sure that this effect will occur in any system with a sawtooth potential, and perhaps in other geometries as well. We are already beginning to investigate new candidates."

Marrying the "bucket brigade" photovoltaic effect in ferroelectrics to the high currents and high efficiencies typical of the best current solar cells could lead to extraordinarily powerful solar-cell arrays in the future, according to the research team.