does not extend far from its source. Indeed, HRP data reveal that 1000 m above the ocean floor the rate of turbulent energy dissipation drops by a factor of 100. Such a steep dependence on depth confines the effect of turbulence-driven mixing to the circulation of bottom and deep waters.

"It's exciting and wonderful physics," says Christopher Garrett of the University of Victoria in British Columbia. Garrett, notes, however, that the tides, rather than being the prime mixing agent, could be a catalyst that interacts with other internal waves, such as those generated by storms on the surface. "But," he adds, "Kurt's model is a bold and significant step forward."

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A Photon-Activated Switch Detects Single Far-Infrared Photons

> The absorption of a single photon can turn the current through a quantum dot on or off.

The far-infrared (FIR) region of the electromagnetic spectrum, covering wavelengths between 10 μm and 1 mm, contains a wealth of information. In the laboratory, this range includes the vibrational and rotational spectra of molecules and the energy gaps of superconductors. And in astrophysics and cosmology, it is the realm of emissions from the earliest galaxies, which, due to their large redshifts, emit more than half of their energy in submillimeter radiation. Also in this spectral range is radiation from protostellar regions and planets, which are too cool to emit in the visible.

Detecting far-infrared radiation is difficult, however. The region falls between radio waves and visible light, and neither set of techniques developed for those regions can be extended readily into the gulf between them. Existing detectors in the far-infrared tend to be either bolometers, which measure the total absorbed power, or heterodyne detectors, which use reference frequencies to mix the absorbed radiation down to lower, more readily managed frequencies. Neither approach comes close to the single-photon sensitivity that is possible with photomultipliers in the visible and near-infrared.

In the first of what may be a new crop of more sensitive FIR detectors, Susumu Komiyama, Takeshi Kutsuwa, and Hiroshi Hirai from the University of Tokyo and Oleg Astafiev and Vladimir Antonov of the Japan Science and Technology Corporation (JST) have recently demonstrated FIR detection at the single-photon level using a novel detection mechanism in a quantum dot.[1] The device was developed as part of JST's Core Research for Evolutional Science and Technology program.

A sensitive electrometer

The device employed by the researchers, illustrated in the accompanying figure, is a semiconducting version of a three-terminal device called a single-electron transistor (SET). (See PHYSICS TODAY, January 1993, page 24.) At its heart is a quantum dot a few hundred nanometers wide, formed in a two-dimensional electron gas by applying negative voltages to electrodes patterned on top of stacked layers of GaAs and AlGaAs. The dot is weakly coupled to source and drain reservoirs through tunnel barriers and cooled in a dilution refrigerator to a temperature of about 50 mK. At this temperature, the behavior of the dot is dominated by the electrostatic energy of charging the dot's various capacitances, and the number of electrons on the dot is well-defined.

The quantum dot is placed in a strong magnetic field, which produces quantized energy levels—Landau levels—whose separation corresponds roughly to the electron cyclotron resonance frequency in the dot. For their detector, the experimenters used magnetic fields for which the lowest Landau level was filled and the second level had a small number of electrons occupying it. The lowest Landau level forms a ring close to the perimeter of the dot, while the second level forms an isolated core in the center. Conduction through the dot takes place through the lowest Landau level—but only when the electrochemical potential of the level lines up with that of the reservoirs.

An additional electrode near the dot functions as a control gate: The experimenters can shift the potential of the dot by changing the bias voltage applied to this electrode, thereby turning the conduction through the dot on and off. As the gate voltage is increased, it periodically pulls another electron onto the dot, producing a regular series of conductance peaks, as shown in the figure on the next page. The strong dependence of the conduction on the gate voltage makes quantum dots, and SETs in general, ultrasensitive electrometers.

Flipping the switch

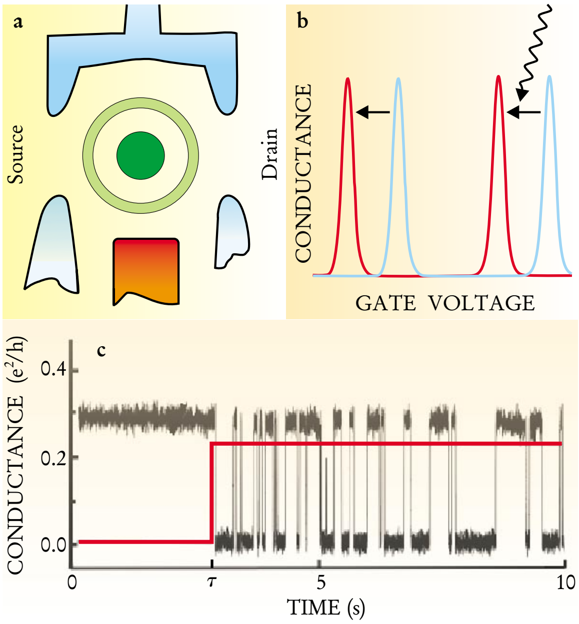
An incoming photon, if its energy is resonant with the Landau level spacing, can promote an electron from the lowest Landau level into the second level—that is, the isolated inner core of the dot. Once excited, the electron stays in the upper level for a long time—ranging from 1 ms to 1000 s or more, depending on the magnetic field—before dropping back down to the lower level. Due to the finite capacitance between the inner core and the outer ring of the dot, the extra charge on the inner core of the dot alters the potential of the lower level, which in turn shifts the values of the gate voltage at which the conductance peaks occur.

The gate voltage shift of the conductance peaks is larger than the widths of the conductance peaks. Thus a dot originally biased to be conducting, or "on," will become nonconducting with the absorption of a single resonant photon. The dot stays "off" until the excited electron drops back down into a vacancy in the lowest Landau level, at which time the dot is reset to its "on" position. A sequence of switching events is shown in the figure's bottom panel.

In traditional photon-assisted tunneling, an absorbed photon leads to the transport of only a few electrons. Here, in contrast, a million or more electrons can flow—or can stop flowing—in response to a single absorbed photon. The dot is sensitive to photons in the far-infrared, with wavelengths of about 200 μm and energies of about 6 meV. The absorption frequency of the detector can be tuned by tweaking the magnetic field, which changes the dot's level spacing.

Other approaches

Similar photon-activated switch behavior in a metallic single-electron transistor was reported in 1995 by



A QUANTUM DOT has been used to detect single far-infrared (FIR) photons. **(a)** The dot is formed in a two-dimensional electron gas. Negatively biased metallic gates (blue) about 700 nm apart confine the electrons laterally. The dot is in a large perpendicular magnetic field, and the electrons in the dot occupy the two lowest Landau levels. The lowest level (light green) forms an outer ring; the second level (dark green) forms an isolated inner core. An additional gate electrode (red) modifies the electrochemical potential of the dot. **(b)** The conduction through the dot (blue curve) is periodic in the voltage applied to the gate electrode. When a FIR photon is absorbed, an electron is excited into the inner core, and the positions of the conductance peaks shift (red). **(c)** Here the gate voltage has been set for an unirradiated conductance peak (a blue peak of **b**). After an FIR source (red) is turned on at time τ, discrete absorption events, which switch off the dot's conductance (black), are observed. (Adapted from ref. 1.)

Jack Hergenrother and his coworkers at Harvard University.[2] Instead of a quantum dot, their device had a small, superconducting island that was connected to normal-metal leads through tunnel junctions and capacitively coupled to a gate electrode. At very low temperatures, the superconducting pairing energy limited the island to only even numbers of electrons. But a sufficiently energetic photon—here, microwave photons of energy 300 μeV—could entice a single, unpaired electron onto the island, enabling current to flow through the island at otherwise nonconducting gate voltages. Direct observation of conductance switching in such a device has yet to be observed, however.

The time resolution in the quantum dot detector experiments is currently limited by the 1 ms time constant of the conductance measurements. Komiyama and his collaborators are investigating using high-speed amplifiers, such as the RF single-electron transistor (RF-SET) electrometer developed by Rob Schoelkopf (Yale University) and his coworkers.[3] This amplifier, which measures the changes in RF power reflected from a metallic SET due to changes in the transistor's gate voltage, has a bandwidth of over 100 MHz and may yield submicrosecond time resolution.

Faster measurement times are not the only ingredient needed to increase the photon counting rate of these devices. As with photomultipliers in the visible and near-infrared, an important characteristic of the quantum dot FIR detector is the time required to reset the device after a photon has been counted. One option to reduce this dead time is to use smaller magnetic fields, which yield shorter lifetimes for the excited electron on the inner core but change the tuning of the detector. A second is to shift the gate voltage to monitor the doubly excited state, in which two electrons have been excited into the second Landau level. Although the coupling to the incident radiation will be smaller for the doubly excited state than the singly excited state, the lifetime of the state is about two orders of magnitude shorter, Komiyama tells us.

Other FIR detection schemes are also under development. Schoelkopf and company have proposed their own FIR detector, which uses an RF-SET to sense the individual pairs of quasiparticles created in a superconductor when FIR photons are absorbed, breaking Cooper pairs.[4] This approach would result in a more broadband FIR detector.

Sensitive FIR detectors will be strongly welcomed by the astronomy community. "Imaging arrays of very sensitive FIR detectors promise to revolutionize observational astronomy," says Harvey Moseley of NASA's Goddard Space Flight Center. "The combination of visible and submillimeter observations will allow us to accurately measure the history of energy release—and hence nucleosynthesis—in the universe as a function of cosmic time."

These detectors may also find other applications, notes Komiyama, such as in near-field microscopy. Recent advances have been reported in the mid-infrared, with wavelengths of 10 μm (see PHYSICS TODAY, July 1999, page 18). "The remaining obstacle for application in the FIR range was the lack of sensitive detectors, which is now resolved in principle by our work," says Komiyama. In any laboratory setting in which such sensitive FIR detectors find application, the radiation source will have to be cold, since the room-temperature blackbody radiation spectrum is peaked in the FIR.

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Survey Halves Estimated Population of Big Near-Earth Asteroids

> NASA's goal is to determine, as soon as possible, the orbits of all asteroids near enough and big enough to threaten cataclysmic damage.

On 1 January 1801, reckoned by sticklers to be the first day of the 19th century, the Sicilian astronomer Giuseppe Piazzi discovered Ceres, the first of the asteroids. With a diameter of almost 1000 km, Ceres remains by far the largest of the known asteroids. Piazzi was searching the region between the orbits of Mars and Jupiter where Bode's law, an empirical formula of the day, said there ought to be an undiscovered planet.

Nowadays there are thought to be