that is genetically transmissible (*5, 6*). Interestingly, these mutations have been found in the α4 and β2 genes. Functional analyses of these mutated nAChRs show that they all display increased sensitivity to the natural neurotransmitter acetylcholine (*7*). The findings of Tapper *et al*. not only provide direct evidence of how nicotine promotes dependence, but also raise fundamental questions about the genetics of addiction. Is it possible that polymorphisms present in the human population could determine our susceptibility to addiction? If this is the case, we can predict that polymorphisms in neuronal nicotinic receptor genes could be associated with tobacco dependence. A coordinated study of polymorphisms in nAChR genes, smoking behavior, and functional characterization of mutated receptors would be required to answer this question.

References

1. A. R. Tapper *et al.*, *Science* **306**, 1029 (2004).
2. N. Le Novere, P. J. Corringer, J. P. Changeux, *J. Neurobiol.* **53**, 447 (2002).
3. C. Lena, J. P. Changeux, *Ann. N. Y. Acad. Sci.* **868**, 611 (1999).
4. S. R. Laviolette, D. van der Kooy, *Nat. Rev. Neurosci.* **5**, 55 (2004).
5. O. K. Steinlein, *Prog. Brain Res.* **145**, 275 (2004).
6. I. E. Scheffer, S. F. Berkovic, *Trends Pharmacol. Sci.* **24**, 428 (2003).
7. D. Bertrand *et al.*, *Epilepsia* **43** (suppl. 5), 112 (2002).

PHYSICS

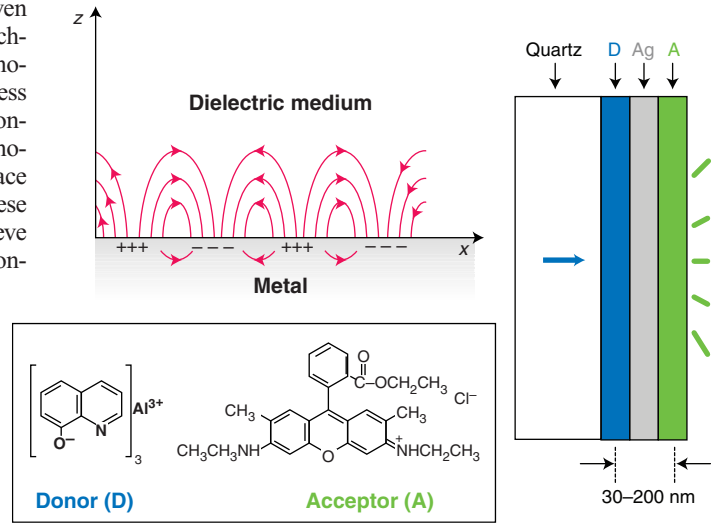
Molecular Plasmonics

Richard P. Van Duyne

Today's information economy is driven by the electronics and photonics technologies, which use electrons and photons, respectively, to carry, store, and process information. An emerging branch of photonics, called plasmonics, aims to use nanostructured materials that support "surface plasmons" (see the figure, top left) for these purposes. Plasmonics can potentially achieve highly complex miniaturized devices by controlling and manipulating light on the nanometer scale (*1*–*3*). Several plasmonic devices—including filters (*1*), wave guides (*1*, *3*), polarizers (*4*), and nanoscopic light source (*5*)—have been demonstrated. However, for plasmonics to reach its full potential, active plasmonic devices (*6*) such as switches and modulators will be required.

On page 1002 of this issue, Andrew and Barnes (*7*) take an important step toward the realization of an active plasmonic device by combining thin polymer films containing molecular chromophores with thin silver films (see the figure). The chromophores are the molecular equivalent of a Wi-Fi transmitter and receiver, transferring energy and hence information across the silver film with the help of surface plasmons.

When light interacts with a free-electron metal, such as a thin (10 to 200 nm) silver film, its surface electrons oscillate collectively and absorb, scatter, or re-radiate the incident photons. The resulting surface electromagnetic field propagates in the plane of the film (the *x* and *y* directions) with ranges of around 10 to 100 μm, but decays exponentially in the *z* direction (see the figure, top left) with a range of 200 to 300 nm. The field intensity in the *z* direction is amplified by a factor of 10 to 100 relative to the incident intensity. These propagating electromagnetic modes are properly termed surface plasmon polaritons, but are often referred to simply as surface plasmons.



Toward active plasmonic devices. (**Top left**) Surface plasmons are surface electromagnetic waves that propagate in the *x*-*y* plane of a metal film but decay exponentially in the *z* direction, both within the film and in the outside dielectric medium. (**Bottom left**) Donor and acceptor molecules used by Andrew and Barnes. (**Right**) Schematic representation of the plasmonic device created by Andrew and Barnes. Light arrives from the left (blue arrow), is absorbed by the donor molecules in the blue layer, and is transferred across the silver film with the help of surface plasmons. The acceptor molecules in the green layer absorb the light and emit their characteristic fluorescence.

The molecular plasmonic device constructed by Andrew and Barnes consists of two polymer layers, one containing donor (D) chromophore molecules and the other containing acceptor (A) fluorophore molecules (see the figure, bottom left). These layers are deposited on either side of a thin (30 to 120 nm) silver film to form a sandwich structure that is supported on a quartz substrate (see the figure, right panel). The donors absorb incident light and transfer this excitation energy by dipole-dipole interactions to the acceptors. The latter then emit their characteristic fluorescence.

The distance dependence of this dipole-dipole interaction, which is commonly referred to as fluorescence resonance energy transfer or FRET, usually places an upper limit of about 10 nm on the distance between D and A (*8*). This length scale is comparable to the dimensions of biological macromolecules. FRET is therefore widely used to measure the distances between sites in biomolecules that are labeled with donors and acceptors. However, a number of biological and physical problems require distance measurements with a range longer than 10 nm. At present this cannot be accomplished by FRET.

Andrew and Barnes show that by coupling surface plasmons and FRET, energy can be transferred with high efficiencies of up to ~70% over distances that are 15 to 20 times longer than the 10 nm observed in free solution or in biomolecules. The authors support the observation of the acceptor emission spectrum with two additional lines of evidence. First, time-resolved measurements of the donor and acceptor emission spectra provide an independent demonstration of surface plasmon–mediated FRET. Second, angle-resolved luminescence studies on samples with a nanofabricated sinusoidal grating etched into the SiO_2 substrate conclusively show the participation of surface plasmon polariton modes.

This groundbreaking research raises a number of important questions. Can other plasmonic nanostructures, such as nanoparticle or nanohole arrays, be fabricated with integrated molecular components to act as switches? What molecular proper-

The author is in the Chemistry Department, Northwestern University, Evanston, IL 60208, USA. E-mail: vanduyne@chem.northwestern.edu

Published by AAAS

ties, such as thermal or light-driven color change, can be used to make active devices? Can other light-driven surface processes be mediated in an analogous manner? Is it possible to use molecular plasmonic nanostructures to measure large distances between sites in biological structures such as viruses and organelles? These and other questions will engage both theorists and experimentalists.

Andrew and Barnes suggest the use of surface plasmon–mediated energy transfer to improve the light output of organic light-emitting diodes, which have great promise as low-cost, flexible, portable displays (*9*, *10*). Surface plasmons may also facilitate charge separation in synthetic light-harvesting nanostructures. Other potential applications for molecular plasmonics include nanoscale optical spectroscopy (*11*), surface-enhanced spectroscopy (*12*), surface plasmon resonance sensing (*13*, *14*), and nanolithography (*15*).

References and Notes

1. W. L. Barnes, A. Dereux, T. W. Ebbesen, *Nature* **424**, 824 (2003).
2. C. L. Haynes *et al.*, *J. Phys. Chem. B* **107**, 7337 (2003).
3. S. A. Maier *et al.*, *Nature Mater.* **2**, 229 (2003).
4. C. L. Haynes, R. P. Van Duyne, *Nano Lett.* **3**, 939 (2003).
5. H. J. Lezec *et al.*, *Science* **297**, 820 (2002).
6. A. V. Krasavin, N. I. Zheludev, *Appl. Phys. Lett.* **84**, 1416 (2004).
7. P. Andrew, W. L. Barnes, *Science* **306**, 1002 (2004).
8. F. Kulzer, M. Orrit, *Annu. Rev. Phys. Chem.* **55**, 585 (2004).
9. L. H. Smith, J. A. Wasey, W. L. Barnes, *Appl. Phys. Lett.* **84**, 2986 (2004).
10. S. Wedge *et al.*, *Appl. Phys. Lett.* **85**, 182 (2004).
11. B. Pettinger *et al.*, *Phys. Rev. Lett.* **92**, 096101 (2004).
12. G. C. Schatz, R. P. Van Duyne, in *Handbook of Vibrational Spectroscopy*, J. M. Chalmers, P. R. Griffiths, Eds. (Wiley, New York, 2002), vol. 1, pp. 759–774.
13. A. J. Haes, R. P. Van Duyne, *Anal. Bioanal. Chem* **379**, 920 (2004).
14. J. M. Brockman, B. P. Nelson, R. M. Corn, *Annu. Rev. Phys. Chem.* **51**, 41 (2000).
15. W. Srituravanich *et al.*, *Nano Lett.* **4**, 1085 (2004).

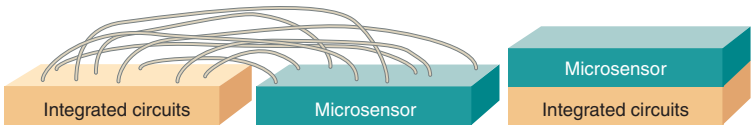
16. Supported by the Air Force Office of Scientific Research Multidisciplinary University Research Initiative program (F49620-02-1-0381) and the National Science Foundation (EEC-0118025, DMR-0076097, CHE-0414554).

PHYSICS

The Best Materials for Tiny, Clever Sensors

Chris Van Hoof, Kris Baert, Ann Witvrouw

Many of today's tiniest sensors are built with microsystems technology, a set of design and production tools that uses techniques similar to integrated circuit production to make micrometer-scale mechanical structures. Since the 1970s, researchers have aimed to create smarter sensors and transducers—in which data are gathered and interpreted within the sensor or transducer—using this technology. From accelerometers and gyroscopes to image and pressure sensors, these smart sensors have higher functionality and performance, are more reliable and often drastically smaller, and can be cheaper to manufacture than conventional sensors.



Side-by-side (left) versus monolithic integration (right) of microsensor and integrated circuit.

In many smart sensors, the sensor and its computational chip may be next to each other (see the figure, left panel). This arrangement is not, however, ideal for all applications. For example, micromirror arrays for projection display applications (*1*) necessitate huge parallelism for controlling the individual elements. They therefore require "monolithic integration" (see the figure, right panel), in which each mirror element is directly interfaced with its processing electronics.

Monolithic integration saves volume, electric power, and possibly cost, but achieving it is not straightforward, because very different materials and processing techniques must be combined on the same substrate. There are currently three approaches to realize monolithic integration of sensors and electronics: processing the microsystems first and the integrated circuits last, typically next to the sensors (*2*); mixing the fabrication of both (*3*, *4*); and processing the integrated circuits first and the microsystems last (*5*, *6*), typically on top of the circuitry.

This third method could be the Holy Grail of smart microsystem processing, because the ability to process and interconnect devices in a modular manner above any underlying signal-processing circuitry is a substantial simplification. Unfortunately, attempts to realize this method by academia and corporate R&D have not had the expected widespread success. Some industry leaders have questioned whether this approach is worth pursuing, because the effort and time needed to develop a generic microsystems module may not be adequately offset by cost savings.

The problem is indeed complex. One needs a good sensor material and a viable process technology for making the sensor, without at the same time affecting or destroying the underlying circuitry (for example, by excessive temperature or by chemical reactions). The major hurdle turns out to be temperature: The finished circuitry cannot withstand temperatures above 450°C—yet the most widely used microsystems material, polysilicon (poly-Si), must be deposited and treated above 800°C to ensure good mechanical and electrical properties. The processes clearly are incompatible.

Many materials, such as organic resists or metals, can be deposited and fabricated into microsystems at low temperatures, but these suffer from degraded device properties, high mechanical stress or stress gradient, and limited reliability. However, one material may combine all the required properties. Poly-SiGe is highly suitable for reliable micromachining because of its high melting point (well above 900°C), high elastic constants (around 150 GPa), and low losses (allowing it to vibrate or resonate if needed) (*6*). By combining chemical vapor deposition and plasma-enhanced chemical vapor deposition, poly-SiGe with mechanical qualities similar to those of the abundant poly-Si can be manufactured at a deposition temperature of 450°C and at adequate deposition rates (100 nm/min) (*7*). Practical films (for example, with a thickness of 10 μm) have been generated with low tensile stress and a very low strain gradient (*7*). In situ doping has led to a poly-SiGe material with low resistivity (*8*). Moreover, the electrical connection to the circuitry shows a reasonable contact resistivity. The good mechanical and electrical properties mentioned above are needed for gyroscopes and other kinematic sensors (such as capacitive accelerometers).

Poly-SiGe therefore seems very suitable for monolithic integration of microsystems

The authors are in the Microsystems Components and Packaging Division, IMEC, Kapeldreef 75, 3001 Leuven, Belgium. E-mail: chris.vanhoof@imec.be