range of 0–35 V to the p–i–n diode. Further work is needed to quantify and confirm the degree of charge-state conversion; a careful tracking of the ratios of the zero-phonon line intensities observed will aid in this regard. Moreover, if this spectral change with applied voltage is due to processes besides NV^- centre charging, these will need to be understood. Finally, as with previous electrostatic studies of NV^- centre charging[2], the work of Kato *et al.* focuses on the ability to convert NV^- states to the NV^0 state. Whether such diode structures can also stabilize the NV^- centre through its optical cycle is an important but yet unanswered question.

Time-resolved techniques are also needed to determine the timescales involved with the gating process. The dynamics of the charge-state modulation are based on charge trapping and may be slow. However, if they could be made fast and strong, extensions of this work could lead to exciting avenues for conversation between spin and charge state, much as there currently are in quantum dots and defect qubits in silicon[5,6].

Another motivation for embedding diamond NV^- centres in p–i–n structures is the integration of quantum spin control into optoelectronic devices like light-emitting diodes. Although in the work of Kato *et al.* electroluminescence from the sample comprised only NV^0-centre emission — the undesired charge state — when increasing the forward bias voltage over 40 V, such integration is a compelling prospect. It could extend the range of environments possible for NV centre-based sensors to become a key component of future devices.

The greatest impact of this study may be the proposed design of a model device for defect systems other than NV^- centres. Gating and optoelectronics may hit a limit in diamond, whose high bandgap and inflexible lattice impede doping. In fact, doping diamond in such a way that it becomes n-type — particularly to the extent demonstrated by Kato *et al.* — is a significant achievement. However, there are many other paramagnetic defect centres hosted by a variety of other semiconductors. In some of these, such as the silicon vacancy or neutral divacancy in silicon carbide, electrical gating could be more effective than in diamond. The upcoming interactions between electrically gateable devices and isolated defect spins should lead to exciting new avenues for quantum devices. ❒

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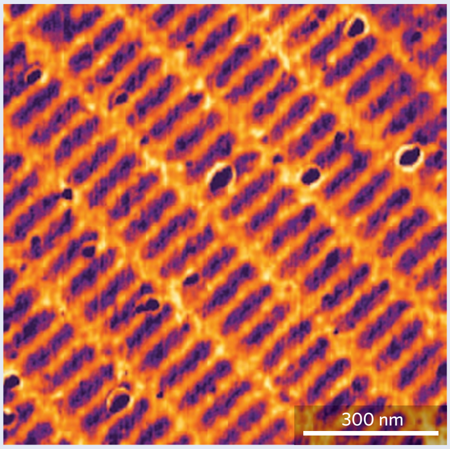
PLASMONICS

Graphene shrinks light

There is an ongoing debate as to whether graphene plasmonics can offer better ratios of light confinement to loss than metal plasmonics. However, the two kinds of plasmonics may be complementary (*Nature Photon.* **7,** 420; 2013). For example, metal plasmons offer strong electromagnetic field confinement at visible wavelengths, but poor confinement at mid-infrared wavelengths. On the other hand, although graphene plasmonics at visible wavelengths is a serious challenge, several groups have demonstrated very strong confinement in the mid-infrared region.

Now, Victor Brar, Harry Atwater and colleagues from the California Institute of Technology have demonstrated graphene plasmon resonators whose smallest structures have dimensions in the range 15–80 nm (*Nano Lett.*, **13,** 2541–2547; 2013). They measured the structural dimensions by atomic force microscopy. Electromagnetic simulations based on the structural measurements predicted that the wavelength of the observed modes may be about 1/100th of that in free space.



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According to Atwater, the Dirac–Fermion band structure of graphene enables the carrier density to be dynamically tuned from nearly zero to 10^{13} carriers per square centimetre. This affects its optical response, allowing the resonance to be tuned across the mid-infrared region of the spectrum; this tunability can be used to effectively turn the resonators on or off for a given excitation wavelength.

Of course, it may be difficult to obtain a strong far-field response from a single small resonator. To overcome this problem, the team fabricated a large array of similar structures. Atwater explained that it was very challenging to reliably fabricate and characterize an array of millions of 15-nm graphene nanostructures over an area that is large enough to permit measurement in a far-field geometry.

"There has been a lot of progress in increasing the carrier density in graphene using ionic liquids and we expect that these higher carrier densities will allow us to push to shorter wavelengths," Atwater told *Nature Photonics*. "However, those methods will probably permit us to obtain only slightly shorter infrared wavelengths, maybe 2 μm. To realize even shorter wavelengths (higher frequencies), more advanced fabrication techniques are needed to make even smaller graphene nanostructures. Conceivably, those techniques can be used to fabricate graphene structures that are 5 nm or smaller, which may make graphene plasmons at optical frequencies feasible. However, quantum effects will begin to play a critical role at those length scales, and the physics will change considerably, which will be interesting."

In the future, the team hopes to increase the mobility of the graphene, reduce the resonator dimensions, and control the edge roughness. This may allow the coupling of emitters and scatterers near graphene resonators to be studied. Atwater also mentioned another interesting direction — the interaction of graphene plasmons with substrates, which will strongly perturb the graphene plasmon dispersion relation.

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