Graphene versus metal plasmons

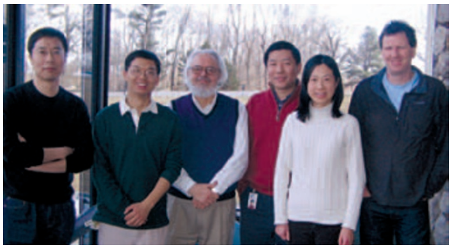
Although there is much debate regarding whether graphene is more suitable than metals for use in plasmonics, the useful operational frequency ranges of these materials are complementary. *Nature Photonics* spoke with Fengnian Xia about his team's recent work on graphene plasmonics.

Why is there so much interest in graphene plasmonics?

The field of plasmonics has been around for a long time, with many of its properties being explored decades ago. Plasmons in both metals and conventional two-dimensional electron gases (2DEGs) have been studied extensively. For the optical community, graphene plasmonics represents a logical extension as it provides a new type of 2DEG for plasmons. A few groups studied graphene plasmons experimentally before our work, whereas graphene plasmon theory was developed by several groups shortly after the discovery of graphene. The theory of graphene plasmons was adapted from that of metals and conventional 2DEGs; there are many similarities, but also some differences. For example, the linear band structure of graphene causes the plasmon mass to depend on the Fermi-level position. Moreover, in metals, parameters that determine the permittivity (such as the conductivity and charge density) and the surface plasmon characteristics (such as the wavenumber and confinement) are fixed, whereas they can be tuned in graphene electrically or by chemical doping. Furthermore, the material parameters of graphene mean that the excitation wavelengths of interest range from the microwave to the mid-infrared regimes. In contrast, plasmons in simple metal structures are mainly in the visible and near-infrared regions because of the optical properties of the noble metals used.

What have you shown in your recent study?

We have investigated plasmon scaling behaviour by fabricating a series of graphene ribbons of different widths and then measuring their plasmonic properties. Ribbons with different widths support localized plasmon oscillations at different frequencies, which correspond to different wave vectors. We were thus able to obtain the plasmon dispersion and examine damping at different plasmon energies, from the terahertz range (~100 μm) to the mid-infrared (a few micrometres). When the ribbon width is small (<100 nm), edge scattering of the plasmons can play an important role in damping. We confirmed that when a ribbon is on a nonpolar substrate the energy dispersion follows the usual scaling rule of a 2DEG. In contrast, when a ribbon is on a polar substrate, a plasmon can couple (hybridize) with the surface polar phonons of the substrate, which strongly modifies the dispersion of the hybrid mode.



VASILI PEREBEINOS

By exciting plasmons on graphene ribbons of different widths, Fengnian Xia and colleagues have been able to investigate loss mechanisms in graphene. From left to right: Fengnian Xia, Hugen Yan, Phaedon Avouris, Tony Low, Wenjuan Zhu and Marcus Freitag. Not in the photograph: Yanqing Wu, Xuesong Li and Francisco Guinea.

We clearly identified the plasmon loss mechanism through the emission of intrinsic graphene optical phonons. This mechanism is very important as it may limit the operational wavelength range of graphene plasmons. This means that below a wavelength of 6 μm, optical-phonon emission reduces the plasmon resonance *Q*-factor. More work is needed to address this potential problem. Coupling to polar substrates is also important. Examination of the dispersion reveals that the coupling of a plasmon to a surface phonon leads to an anticrossing and the creation of energy gaps in the dispersion spectrum. We hence directly visualize the coupling strengths of electrons and surface polar phonon modes on the polar substrate. This might be important for microelectronics as we seek different polar substrates for new high-*k* dielectrics. By investigating this kind of coupling, we may be able to improve transistor performance.

Which gives better plasmonic waveguiding with high confinement, metals or graphene?

Applications that require both strong electromagnetic field confinement and very long propagation lengths are difficult to implement using graphene plasmonics, according to the work done by us and other groups. When you have very strong confinement, the propagation length is limited to a couple of surface plasmon wavelengths. Metals have the same problem. For example, if a simple silver–air interface is used for high confinement (which occurs at a free-space wavelength of around 350 nm), the propagation length of the surface plasmon mode can be shorter than a few surface plasmon–polariton wavelengths. Although it is possible to introduce a gain medium, this is very difficult to achieve in mid-infrared and terahertz regimes. However, with graphene, it should be possible to reduce losses by improving the quality of graphene. I don't think we have produced graphene of the highest possible quality yet. We may be able to increase the propagation length from a few wavelengths to tens of wavelengths. For both metals and graphene, if you want strong confinement well below the diffraction limit, the propagation length will be limited. But again, graphene has the potential to be improved and has the unique advantage of tunability.

Why have large variations been reported for the properties of the waves?

In their estimates, researchers may use very different values for the properties of graphene. These data are based on real systems, but they have generally been obtained under a wide variety of conditions. In our work, we used a chemical-vapour-deposited graphene sample that was tens of centimetres in dimension, fabricated numerous ribbon arrays, performed all measurements at room temperature and introduced controlled doping to obtain the plasmon resonance frequency accurately. In addition, our work shed more light on the origin of plasmon damping, which is currently not well understood.

INTERVIEW BY DAVID PILE

Fengnian Xia and colleagues have an Article about plasmon damping in graphene on page 394 of this issue.