The Effects of Surfaces and Surface Passivation on the Electrical Properties of Nanowires and Other Nanostructures: Time-Resolved Terahertz Spectroscopy Studies

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***Abstract*—The electrical properties of nanomaterials are strongly influenced by their surfaces, which in turn are strongly influenced by device processing and passivation procedures. Optical pump–terahertz probe spectroscopy is ideal for measuring the native properties of these materials, determining the changes induced by device processing, and studying the effectiveness of surface passivation procedures. Here we study the electronic properties of III–V nanowires and other nanomaterials in both their native and encapsulated/integrated states, which is uniquely possible with terahertz spectroscopy.**

I. Introduction

NANOMATERIALS, such as III–V nanowires and graphene, feature large surface area-to-volume ratios and consequently their surfaces can dominate their electronic properies. Surface states, combined with surface roughness, and the dielectric environment, can degrade a nanomaterial's electronic properties such as charge carrier mobility and lifetime. In addition, surface states can cause band-bending and depletion or accumulation of carriers in the nanomaterial. Device-based measurements, such as Hall effect and field effect measurements, are only possible after the nanomaterial has undergone a series of device processing steps (electron microscopy, resist deposition, lithography, deposition of contacts, etc), which themselves significantly affect the surface of the nanomaterial. This means that with device-based measurements, it is difficult to disentangle the native properties of the nanomaterials from the effects of processing. Optical pump–terahertz probe (OPTP) spectroscopy, as a contact-free measurement technique, overcomes this difficultly. Using OPTP spectroscopy it is possible to characterise nanomaterials before and after processing, and thereby both ascertain their native properties and ascribe changes to processing. OPTP measurements are also guiding the optimisation of surface passivation processes.

II. Results

III–V nanowires of various diameters were grown via either metalorganic chemical vapour deposition or molecular beam epitaxy. Diameter-dependent measurements of photoconductivity reveal that smaller diameter nanowires experience more rapid photoconductivity decays. This points to surface recombination as a major recombination pathway. In nanowires, the charge carrier lifetime τ tends to follow the relationship

$$\frac{1}{\tau} = \frac{1}{\tau_{bulk}} + \frac{4S}{d}$$

where τ_{bulk} is the lifetime in a bulk material without any contribution from surface recombination, S is the surface recombination velocity, and d is the nanowire diameter. In some nanowires, the surface traps are saturable, which gives rise to decay kinetics that slow with time after photoexcitation and slow with increasing photoexcitation fluence. This phenomenon is seen in the photoconductivity decay kinetics of GaAs nanowires (Fig. 1).

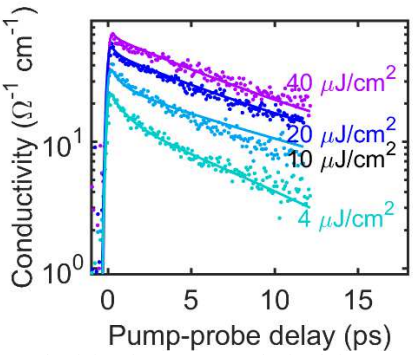

Fig. 1. Photoconductivity decay curves obtained from GaAs nanowires of 80 nm diameter after photoexcitation with a pump pulse centred at 800 nm of fluence between 4 and 40 μJ cm^2. The fits follow the saturable trapping model described in Reference [1].

Electron mobilities were extracted by fitting Drude-Lorentz fits to terahertz photoconductivity spectra. GaAs nanowires of narrower diameter exhibited lower electron mobilities due to increased carrier scattering at the nanowire surface [1]. Passivation with thick layers of lattice-matched AlGaAs was effective in increasing both the electron mobility and the charge carrier lifetime in the GaAs cores [2]. Passivation of InAsP nanowires with ultrathin InP shells was effective at increasing the charge carrier lifetime in the InAsP cores [3]. However, this approach yielded no improvement in electron mobility possibly because the expected reduction in surface-scattering due to passivation was counteracted by the strain due to the lattice-mismatched InP shell [3].

Alumina deposited by atomic layer deposition (ALD) was also shown to be highly effective in passivating the surfaces of InAs nanowires [4] and controlling the electronic properties of graphene [5]. Specifically, the trimethylaluminium precursor is thought to chemically reduce surface oxides on InAs nanowires and remove hydroxyl groups from the substrates hosting graphene.

III. Conclusion

OPTP spectroscopy has revealed that a variety of different surface passivation approaches can improve charge carrier transport in III–V nanowires. These findings are expediting device development.

Acknowledgements

This work was funded by ERC Starting Grant ACrossWire (Grant Agreement 716471). S.O.A. thanks the EPSRC for her International Doctoral Studentship.

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