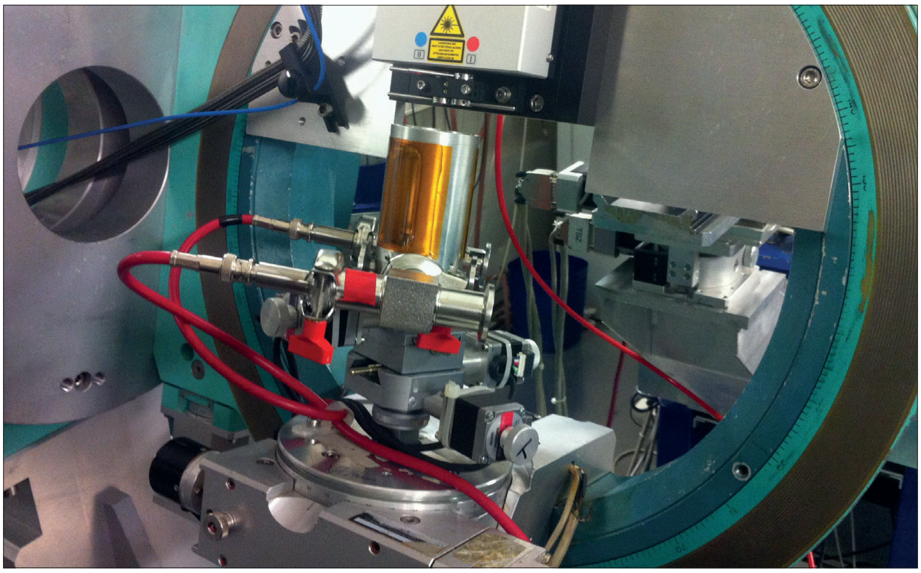
Nano-piezoelectrics

Mechanical promise for Moore's law

A decade of stagnation in computing speeds may be about to give way to the biggest step change in processing power in history thanks to a new project called Nanostrain that seeks to develop nanoscale piezoelectric transistors, explains **Markys Cain**


NPL/XMaS

Precision tool By subjecting materials to synchrotron X-rays in sample environments like this one at the XMaS beamline at the ESRF, the Nanostrain team will be able to measure strain at the atomic level.

Over the past 40 years, advances in semiconductor-processing techniques have vastly reduced the size and improved the capabilities of microelectronic devices. In accordance with Moore's law, the dimensions of individual devices in an integrated circuit have been steadily halving every two years or so. Today's processor chips contain more than a billion transistors compared with around a million in Intel's ground-breaking Pentium processor of the early 1990s.

But the rate of miniaturization of the basic building blocks of modern electronics – based on complementary metal–oxide–silicon (CMOS) technology – is tailing off and computer processing speeds have stagnated for the past decade. Further scaling down of CMOS devices faces serious difficulties owing to leakage currents, passive power dissipation and other detrimental effects. Indeed, CMOS switching speeds are now power limited: you cannot remove heat from a chip fast enough before the device melts. Unless we can reduce the effective operating voltage of the switch, then this limit (which is intrinsic to material properties such as loss and impedance) cannot be overcome.

Faster computational speeds, reduced device weight and lower energy consumption could, however, all be within reach if the excitement around a new transistor based on piezoelectric materials can be turned into technological reality. Piezoelectric transistors could operate at a 10th of the voltage of today's CMOS equivalent, consuming 100 times less power, and be switched at much faster rates. With the US electronics giant IBM having recently filed the first patents for piezoelectric transistors, European physicists, materials scientists and metrologists have joined forces in a project called Nanostrain to develop novel electronic devices based on controlling strain at the nanometre scale. Launched in late 2013, the three-year, €4m ($5.7m) project funded by the European Union's European Metrology Research Programme under the direction of "EURAMET" aims to take us beyond Moore's law to faster, more reliable and greener computing.

Shape-shifting

Piezoelectric materials exhibit a close relationship between their mechanical and electrical properties. Applying a voltage, for example, reorients the molecular dipole moments, and causes rotational and translational strains in the complex domain structures found in many such materials, resulting in a net macroscopic change in shape. Because this relationship is reversible, strain generated by a piezoelectric actuator can deliver sufficient force to cause a "piezoresistive" material to switch from being an insulator to a conductor and back again, offering the possibility of reading and writing digital information.

Although carbon nanotubes also display large changes in resistance depending on the chirality of the tube, piezoelectric materials have been around for far longer, which means that we can benefit from our much greater scientific understanding of them. Indeed, piezoelectrics are already used in a wide range of commercial settings, including car engines and in production lines where they act as energy harvesters that turn mechanical strain into a power source for autonomous sensors.

Several paths are currently being explored to try to end the stagnation of CMOS transistor speeds. These include spintronics, in which the spin of electrons as well as their charge would be used to process information, and quantum computers that harness the non-classical rules of superposition and entanglement. But it is only recently that researchers have considered using the mechanical properties of materials to control changes in transistor technology.

Specifically, interest in such materials took off in 2012 when IBM developed the first piezoelectric-effect transistor (PET). The prototype device consisted of a piezoresistive material clamped between a slab of piezoelectric material and a rigid frame made from a nano-indenter and a sapphire plate. The resulting microscale sandwich can switch between an overall conducting and an insulating state by applying a voltage, which changes the morphology of the piezoelectric layer such that it exerts a very large strain-induced stress on the piezoresistive material.

This sequence of events occurs nearly instantly (on picosecond timescales) and far more efficiently than the laws of physics allow for CMOS transistors. The big question for the Nanostrain team concerns scalability. Do these attractive properties replicate down to the scale of CMOS transistors?

Despite the undoubted potential of piezoresistive electronics, the success of the technology relies on the development of new and more accurate techniques to characterize these materials at the nanoscale. To address this final piece of the jigsaw, Nanostrain brings together European national laboratories, world-class research

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Three Postdoctoral positions (Research Associates, each for 3 years) are available at the Lancaster Centre for Nanoscale Dynamics [http://www.physics.lancs.ac.uk/research/centre-for-nanoscale-dynamics], for theoretical research in fundamental physical properties of atomic two-dimensional crystals (including graphene, boron nitride, chalcogenides of various metal, etc.) and modelling electronics and optoelectronics devices based hybrid structures of such materials. Theoretical work will be coordinated with a massive experimental effort in the European Graphene Flagship and ERC Synergy Grant Hetero2D. Applicants should hold or be close to acquiring a PhD in theoretical physics with specialisation in the theory of two-dimensional materials (analytical and/or density functional theory), mesoscopic physics using quantum transport theory and Green functions; strongly correlated systems; or quantum optics. The initial search closes on 30 May, 2014 (http://hr-jobs.lancs.ac.uk/Vacancy.aspx?ref=A971): after that, directly contact Prof V Fal'ko [v.falko@lancaster.ac.uk].

Fully-funded studentship for **PhD in Experimental Nanoscience** (http://www.physics.lancs.ac.uk/study_here/postgraduate/phd-in-nanoscience) is available to work on the project on graphene-based multilayer structures and devices. Graphene will be combined with other 2D materials (boron nitride, dichalcogenides of transitional metals and layered high-Tc superconductors). The project will be carried out at the state-of-the-art nanofabrication facility at Lancaster Quantum Technology Centre (http://www.qtc.lancs.ac.uk/) and will involve magneto-transport measurements at low temperatures. The studentship is for 3.5 years for (UK/EU), 3 years (OS). For details, contact Dr L Ponomarenko [l.ponomarenko@lancaster.ac.uk].

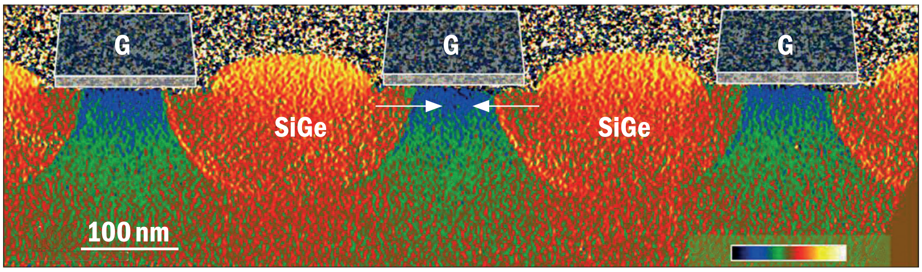
Fully-funded studentship for **PhD in Experimental Nanoscience** (http://www.physics.lancs.ac.uk/study_here/postgraduate/phd-in-nanoscience) is available in the Nanoscale Microscopy Group (www.nano-science.com) at Lancaster, to work on Nanoscale Thermal Metrology, to explore fundamental mechanisms of nanoscale heat transport in materials and nanoscale devices using advanced scanning thermal microscopy. This project is a part of a European network QUANTIHEAT. The position is for 3.5 years. For details, contact Dr O Kolosov [o.kolosov@lancaster.ac.uk].

CDT GrapheneNOWNANO is a newly established Centre for Doctoral Training , jointly run by the University of Manchester and Lancaster University. It builds on the world-leading expertise in the science and technology of graphene and other two-dimensional (2D) materials available on the two campuses, where staff offer a broad range of project on fundamental science and technology of graphene and 2D material, and their applications ranging from optoelectronics to biomedical. Visit www.graphene-nownano.manchester.ac.uk for information on the training programme and admissions process. For information on the Manchester site of the CDT, email to graphene-nownano@manchester.ac.uk; details on the Lancaster site can be obtained from Prof V Fal'ko [v.falko@lancaster.ac.uk].

GRAPHENE NOWNANO CDT

instrument facilities and companies to provide highly accurate measurements and a unique set of methodologies to help drive the commercialization of next-generation electronic devices.

We plan to make measurements at small length scales under industrially relevant conditions such as high stress and electric fields, and the results will be made available for other piezoelectric applications to benefit. These include ultra-high-speed and resolution printing, chemical and optical sensors, telecommunications, and innovative electronics in the automotive, power, oil and gas, and medical sectors. The Nanostrain project will, we believe, have a profound impact on a number of different fields through improved understanding of piezomaterials and new metrology capabilities at the nanoscale.



NPG

Taking the strain Strain distribution from a standard transistor array measured by dark-field electron holography, demonstrating how the technique can be used to visualize strain in piezoelectric transistors.

Multiple techniques

The project has been divided into several key research areas. At the UK's National Physical Laboratory (NPL), Carlo Vecchini and colleagues will use a combination of X-ray diffraction and optical interferometry to measure displacements (and hence strain) in very-small-scale piezoelectric materials. A major aspect of this work is the use of synchrotron X-rays via a partnership between the universities of Warwick and Liverpool with the "XMaS" beamline facility at the European Synchrotron Radiation Facility (ESRF) in Grenoble. These techniques have never been combined and they will allow strain at the atomic level (as measured from crystallographic information such as lattice changes, phase transformations and ionic displacements as a function of applied voltage) and macroscopic displacements from the nanometre to the micrometre level to be measured in the same sample at the same time.

It is not without its challenges, however. Interferometry is very sensitive to vibrations and other environmental factors, whereas synchrotron X-ray measurements are typically performed in a noisy environment surrounded by vacuum pumps and involve continuous movements of the sample to fulfil different X-ray diffraction conditions. As a result, the NPL team, working with commercial partner SIOS in Germany, is building a differential sample-reference surface-interferometer system to mitigate and correct for vibrations.

Once the set-up is in place in autumn this year, we expect to be able to capture displacement measurements at length scales spanning eight orders of magnitude. This will take our understanding of current micron-scale PET set-ups down to the nanometre scale of CMOS components, providing valuable insights to help engineer new materials and

devices. The measurement programme will also include the effect of other factors such as temperature, magnetic field and switching frequency. Although PETs are expected to reduce the operating temperatures of chips, higher switching frequencies will create heat that increases the operational temperature and could affect performance and durability.

In France, meanwhile, Martin Hytch and co-workers at the Centre d'Elaboration de Matériaux et d'Etudes Structurales in Toulouse will use destructive methods such as transmission electron microscopy (TEM), novel holographic TEM and scanning electron microscopy to measure the electric-field-induced strain in piezoelectric materials and compare it with theoretical models. TEM holography, which provides a map of how strain varies across a sample rather than just measuring it in one place, provides micron-scale fields of view at nanometre spatial resolution.

The third major prong of the Nanostrain project will be carried out at Germany's Physikalisch-Technische Bundesanstalt (PTB) by Peter Hermann and colleagues, who will make unprecedented high-precision strain measurements based on Raman and infrared spectroscopy techniques. Raman spectroscopy uses monochromatic laser light to excite particular vibrational and rotational transitions in molecules or lattice vibrations in crystals, providing information about the spatial chemical and stress distribution.

The complementary technique of infrared scanning near-field optical microscopy, which is sensitive to the change of dipole moment during vibrations, can achieve a spatial resolution significantly below 100 nm. Broadband synchrotron-radiation infrared spectroscopy, meanwhile, allows measurements to be performed over a much broader spectral range than by using conventional laser sources.

Finally, a range of modelling and visualization techniques, including atomic simulations, finite-element and continuum modelling, as well as digital image correlation, will be used to understand and characterize the properties of piezoelectric devices across different length scales. This work will be led by Anna Kimmel and colleagues from NPL in partnership with researchers at PTB, the BAM Federal Institute for Materials Research and Testing in Germany, and the Czech Metrology Institute.

Investigating the scalability of PET transistors could unlock one of the most exciting new areas of materials science and electronics R&D for decades. If experimental results match what we expect from theory, the impact could be seen within the next two decades and will directly influence our experience and enjoyment of all computing and electronics devices, as well as opening up new areas of scientific discovery through faster data processing.

Although we have known about conventional piezoelectric materials for some time, modern manufacturing techniques make it possible to create new high-performance versions. To understand the behaviour, stability and performance of these and other materials it is crucial that we can study them at the nanoscale because microstructural defects and interfaces, not to mention geometrical constraints, define the properties of entire nanostructures.

After decades of scaling the heights of processing power, CMOS technology has now reached a limit beyond which the laws of physics provide an impenetrable ceiling. It is a measure of the ingenuity of science to find another route to higher levels of speed: a new technology to be refined and a new area of physics to be opened for investigation.

Markys Cain is leader of the Nanostrain project at the National Physical Laboratory, e-mail markys.cain@npl.co.uk

ADVENT
RESEARCH MATERIALS

Element Name
Atomic No. Symbol
Atomic weight
Density ← Solids & **Liquids** (g/cm³) Gases(g/l)
M.pt./B.pt.(˚C) ← Melting point (Solids & **Liquids**) • Boiling point (Gases)

🟨 Standard Catalogue Items

Periodic Table of the Elements

1	2		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Hydrogen 1 H 1.0079 0.090 -252.87																		Helium 2 He 4.0026 0.177 -268.93
Lithium 3 Li 6.941 0.54 180.5	Beryllium 4 Be 9.0122 1.85 1287												Boron 5 B 10.811 2.46 2076	Carbon 6 C 12.011 2.27 3900	Nitrogen 7 N 14.007 1.251 -195.79	Oxygen 8 O 15.999 1.429 -182.95	Fluorine 9 F 18.998 1.696 -188.12	Neon 10 Ne 20.180 0.900 -246.08
Sodium 11 Na 22.990 0.97 97.7	Magnesium 12 Mg 24.305 1.74 650												Aluminium 13 Al 26.982 2.70 660.3	Silicon 14 Si 28.086 2.33 1414	Phosphorus 15 P 30.974 1.82 44.2	Sulphur 16 S 32.065 1.96 115.2	Chlorine 17 Cl 35.453 3.214 -34.04	Argon 18 Ar 39.948 1.784 -185.85
Potassium 19 K 39.098 0.86 63.4	Calcium 20 Ca 40.078 1.55 842		Scandium 21 Sc 44.956 2.99 1541	Titanium 22 Ti 47.867 4.51 1668	Vanadium 23 V 50.942 6.11 1910	Chromium 24 Cr 51.996 7.14 1907	Manganese 25 Mn 54.938 7.47 1246	Iron 26 Fe 55.845 7.87 1538	Cobalt 27 Co 58.933 8.90 1495	Nickel 28 Ni 58.693 8.91 1455	Copper 29 Cu 63.546 8.92 1084.6	Zinc 30 Zn 65.39 7.14 419.5	Gallium 31 Ga 69.723 5.90 29.8	Germanium 32 Ge 72.64 5.32 938.3	Arsenic 33 As 74.922 5.73 816.9	Selenium 34 Se 78.96 4.82 221	Bromine 35 Br 79.904 **3.12** **-7.3**	Krypton 36 Kr 83.80 3.733 -153.22
Rubidium 37 Rb 85.468 1.53 39.3	Strontium 38 Sr 87.62 2.63 777		Yttrium 39 Y 88.906 4.47 1526	Zirconium 40 Zr 91.224 6.51 1855	Niobium 41 Nb 92.906 8.57 2477	Molybdenum 42 Mo 95.94 10.28 2623	Technetium 43 Tc [98] 11.5 ☢ 2157	Ruthenium 44 Ru 101.07 12.37 2334	Rhodium 45 Rh 102.91 12.45 1964	Palladium 46 Pd 106.42 12.02 1554.9	Silver 47 Ag 107.87 10.49 961.8	Cadmium 48 Cd 112.41 8.65 321.1	Indium 49 In 114.82 7.31 156.6	Tin 50 Sn 118.71 7.31 231.9	Antimony 51 Sb 121.76 6.70 630.6	Tellurium 52 Te 127.60 6.24 449.5	Iodine 53 I 126.90 4.94 113.7	Xenon 54 Xe 131.29 5.887 -108.05
Caesium 55 Cs 132.91 1.88 28.4	Barium 56 Ba 137.33 3.51 727	57-70 *	Lutetium 71 Lu 174.97 9.84 1652	Hafnium 72 Hf 178.49 13.31 2233	Tantalum 73 Ta 180.95 16.65 3017	Tungsten 74 W 183.84 19.25 3422	Rhenium 75 Re 186.21 21.02 3186	Osmium 76 Os 190.23 22.61 3033	Iridium 77 Ir 192.22 22.65 2466	Platinum 78 Pt 195.08 21.09 1768.3	Gold 79 Au 196.97 19.30 1064.2	Mercury 80 Hg 200.59 **13.55** **-38.83**	Thallium 81 Tl 204.38 11.85 304	Lead 82 Pb 207.2 11.34 327.5	Bismuth 83 Bi 208.98 9.78 271.3	Polonium 84 Po [209] 9.20 ☢ 254	Astatine 85 At [210] – ☢ 302	Radon 86 Rn [222] 9.73 ☢ -61.85
Francium 87 Fr [223] – ☢ –	Radium 88 Ra [226] 5.0 ☢ 700	89-102 **	Lawrencium 103 Lr [262] – ☢ 1627	Rutherfordium 104 Rf [265] – ☢ –	Dubnium 105 Db [268] – ☢ –	Seaborgium 106 Sg [271] – ☢ –	Bohrium 107 Bh [272] – ☢ –	Hassium 108 Hs [270] – ☢ –	Meitnerium 109 Mt [276] – ☢ –	Darmstadtium 110 Ds [281] – ☢ –	Roentgenium 111 Rg [280] – ☢ –	Copernicium 112 Cn [285] – ☢ –	Ununtrium 113 Uut [284] – ☢ –	Ununquadium 114 Uuq [289] – ☢ –	Ununpentium 115 Uup [288] – ☢ –	Ununhexium 116 Uuh [293] – ☢ –	Ununseptium 117 Uus [–] – ☢ –	Ununoctium 118 Uuo [294] – ☢ –

*Lanthanoids	Lanthanum 57 La 138.91 6.146 920	Cerium 58 Ce 140.12 6.689 795	Praseodymium 59 Pr 140.91 6.64 935	Neodymium 60 Nd 144.24 6.80 1024	Promethium 61 Pm [145] 7.264 ☢ 1100	Samarium 62 Sm 150.36 7.353 1072	Europium 63 Eu 151.96 5.244 826	Gadolinium 64 Gd 157.25 7.901 1312	Terbium 65 Tb 158.93 8.219 1356	Dysprosium 66 Dy 162.50 8.551 1407	Holmium 67 Ho 164.93 8.795 1461	Erbium 68 Er 167.26 9.066 1497	Thulium 69 Tm 168.93 9.321 1545	Ytterbium 70 Yb 173.04 6.57 824
**Actinoids	Actinium 89 Ac [227] 10.07 ☢ 1050	Thorium 90 Th 232.04 11.72 ☢ 1842	Protactinium 91 Pa 231.04 15.37 ☢ 1568	Uranium 92 U 238.03 19.05 ☢ 1132	Neptunium 93 Np [237] 20.45 ☢ 637	Plutonium 94 Pu [244] 19.816 ☢ 639	Americium 95 Am [243] – ☢ 1176	Curium 96 Cm [247] 13.51 ☢ 1340	Berkelium 97 Bk [247] 14.78 ☢ 986	Californium 98 Cf [251] 15.1 ☢ 900	Einsteinium 99 Es [252] – ☢ 860	Fermium 100 Fm [257] – ☢ 1527	Mendelevium 101 Md [258] – ☢ 827	Nobelium 102 No [259] – ☢ 827

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