Human resources for future alternative-energy research

To the Editor – We face, after over two decades of not-so-benign neglect, a serious deficit of alternative-energy (AE)-oriented basic science researchers. Indeed, a major problem in meeting the global energy challenge may well be the paucity of top scientists pursuing AE-related research problems. This deficit has the potential to self-proliferate, because a limited core of experienced researchers will encourage a limited group of talented students and post-docs to seek research opportunities in AE research in the future.

In early September 2007, Israeli scientists performed an 'experiment' to break out of this pattern: A selected group of 24 of the nation's top, final-year PhD students from all areas of physical, life and engineering sciences, assembled in a tranquil Galilee mountain location, along with 20 senior Israeli and foreign scientists, who are all experts in various aspects of AE or in directly relevant core areas. Most students didn't have any previous AE experience, but had showed a clear interest in the subject. The meeting (www.weizmann.ac.il/conferences/ASEO/) funded by the Bat-Sheva de Rothschild foundation, with support from the Safed foundation, the Mizpe Yamim hotel and our parent institutions, had a rather conventional name: 'Alternative, Sustainable Energy Options'. But there was nothing conventional about the programme and atmosphere of the meeting.

After a packed two-day crash course of general presentations by experts, explaining AE issues "from fundamentals to engineering", the group split into smaller sets and was introduced to systematic innovative thinking approaches. In each of the smaller groups, dynamic discussions and brain-storming sessions developed, interspersed by intense tutoring by the senior scientists in their areas of expertise (see Fig. 1). The final discussion sessions were led by students on topics they proposed, such as: "is there really a crisis in energy resources?"; "is there an ideal electrical storage approach?"; and "theoretical limit(s) of biological solutions to the energy challenge".

Figure 1 Tutoring from the senior scientists. Left picture: David Cahen (far right) from Weizmann Institute, Israel and Uri Sivan (second right), Technion, Israel. Right picture: Peter Atkins (second right), Oxford University, UK, with the 'ideas and questions' boards in the background.

Students and lecturers admitted to being initially sceptical about the non-conventional seminar programme, but the 'pleasant week in a nice place' expectations were surpassed by intense days of discussions, focused personal tutoring and plenty of lively arguments. "The seminar made us aware of, and knowledgeable about, the energy challenges and related worldwide scientific research, but it also allowed us to form our own opinions about directions for fruitful avenues of research for possible new approaches to AE," was the response from one student.

How large a new cadre of energy researchers will develop as a result of the meeting remains to be seen, but it seems clear that its first seeds could have been planted on a beautiful, peaceful Galilee mountain side. Our message to all our colleagues is that investing some time and effort now in such projects should help us all to a brighter future, by introducing a new generation to AE research.

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A one-cent room-temperature magnetoelectric sensor

To the Editor — Advances in one area can unwittingly produce improvements in an entirely different field. Industrially manufactured multilayer capacitors (MLCs) are 1-cent electronic components[1] (Fig. 1a,b) that now contain ferromagnetic nickel because it is cheap. We show that MLCs therefore inadvertently function as room-temperature (RT) magnetic field sensors that require no electrical power.

There is great scientific interest at the moment[2,3] in the magnetoelectric (ME) coupling of magnetic and electrical order parameters. However, suggested applications[2] in, for example, transducers and data storage have not been forthcoming because single-phase materials perform poorly[2,3], and the exploitation of large strain-mediated[2,3] coupling between two phases requires development work and the identification of end users. Relevant development work has unwittingly been performed in MLCs based on $BaTiO_3$, via the cost-saving replacement of Ag/Pd with Ni in the electrodes.

In a vibrating sample magnetometer, with electrical access[4] to the sample from a digital multimeter and a d.c. power supply, quasi-static ME measurements were performed on a '1206' MLC (0.6 μF, AVX, Northern Ireland) with 81 parallel capacitors (each of active area 4.5 mm²) formed from interdigitated Ni-based electrodes (1.5 μm thick) separated by $BaTiO_3$-based dielectric layers (9.8 μm thick); Fig. 1b.

Figure 1c shows direct and reproducible ME effects $V(H)$, where V is the voltage response to an applied magnetic field H. Magnetization $M(H)$ behaves similarly, confirming strain-mediated coupling by Ni

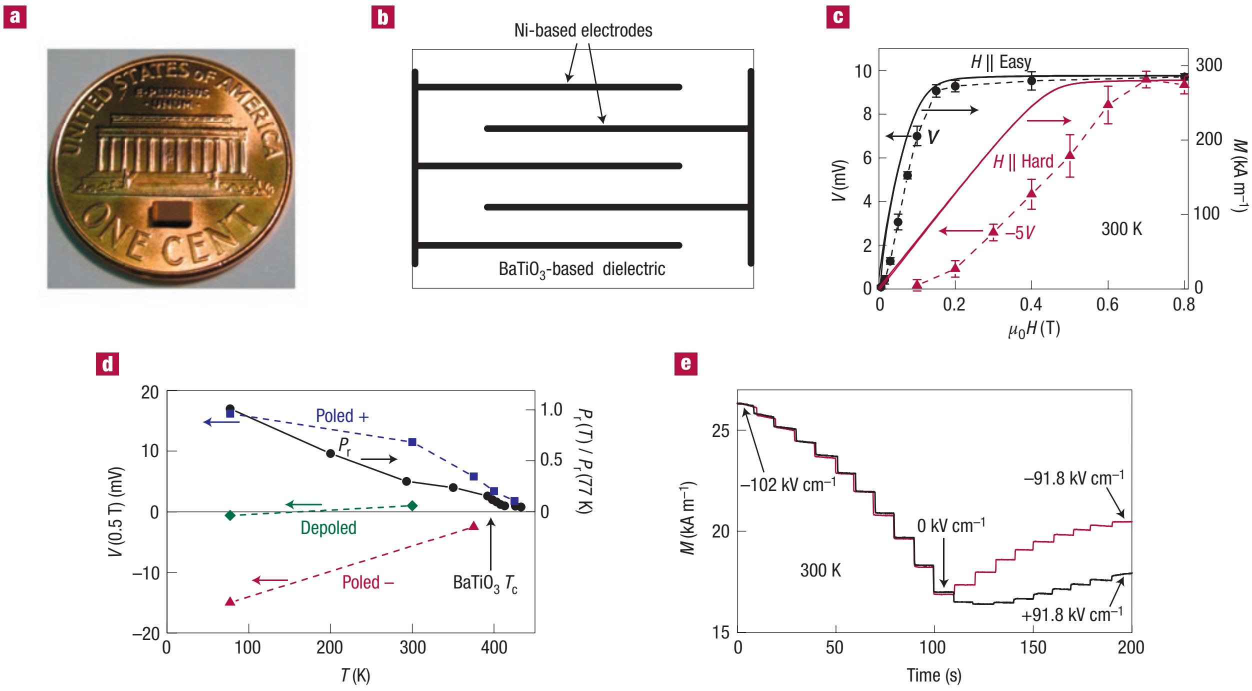

Figure 1 ME coupling in an MLC based on $BaTiO_3$ with interdigitating Ni-based electrodes. All dashed lines are guides to the eye. **a**, MLC size and cost comparison. **b**, Schematic MLC cross-section. A magnetic easy axis lies in the electrode plane, and the out-of-plane direction is hard. **c**,**d**, direct ME data $V(H)$ averaged over six runs after poling in $E = 102$ kV cm^{-1} (**c**) and ±102 kV cm^{-1} (**d**), and discharging. **c**, $V(H)$ at 300 K and the MLC magnetization $M(H)$ have a similar form for $H||$ easy or hard. $V(H) = V(-H)$. **d**, $V(0.5\ T)$ with $H||$ easy tracks the remanent MLC polarization $P_r(T)$ (measured from 50 Hz $P(E)$ loops to ±4.9 kV cm^{-1}). Data after depoling are also presented. **e**, Converse ME data $M(E)$ at 300 K in $H = 0$ are established by plotting $M(t)$ and changing $|E|$ by 10.2 kV cm^{-1} every ~10 s (black line: -102 kV cm^{-1} → +91.8 kV cm^{-1}, red line: –102 kV cm^{-1} → 0 → –91.8 kV cm^{-1}). Before time $t = 0$, the MLC was saturated in $\mu_0 H = 0.5$ T and $E = -102$ kV cm^{-1}. $H||M||$ easy; M normalized using electrode volume; current <10 nA several seconds after each change of E.

magnetostriction. The maximum sensitivity dV/dH is 7.0×10^{-6} V Oe^{-1}, that is, 0.1 T generates 7 mV. The MLC is in effect less sensitive than a SQUID, but operates at RT and only costs 1 cent. The sensitivity of an expensive (larger) sandwich structure using optimal materials (Terfenol-D and single-crystal $Pb(Mg,Nb)O_3$-$PbTiO_3$)[5] is 10^5 times larger, but its ME coupling constant is only 10^3 times larger than the MLC value ($dE/dH = 7.1 \times 10^{-3}$ V cm^{-1} Oe^{-1}) where E is electric field. The geometrically calculated dielectric constant is 1823, giving $dP/dH = 1.4 \times 10^{-10}$ s m^{-1}, where P is polarization.

Figure 1d shows $V(0.5\ T)$ with H parallel to the magnetic easy axis after different electrical poling histories, at selected temperatures. The weak temperature dependence around RT is attractive for applications. The observed dependence of $V(0.5\ T)$ on both poling history and remnant polarization P_r (Fig. 1d) reflects the ferroelectric nature of the doped $BaTiO_3$. Ferroelectricity breaks device symmetry, and guarantees piezoelectricity for strain-mediated coupling. Compared with pure $BaTiO_3$, P_r is suppressed but the Curie temperature (T_C) is similar (Fig. 1d).

Figure 1e shows converse ME effects $M(E)$. Sharp changes in M of, for example, 7.2% at 100 s ($\mu_0 dM/dE = 1.9 \times 10^{-9}$ s m^{-1}) compare favourably with the 26% ($\mu_0 dM/dE = 2.21 \times 10^{-8}$ s m^{-1}) seen[4] at RT for an epitaxial $La_{0.67}Sr_{0.33}MnO_3$ film on single-crystal $BaTiO_3$ (μ_0 is the permeability of free space).

Geometrically, MLCs are inadvertently well-designed ME transducers because their laminar structure simplifies strain fields and thus enhances coupling[4]; their large capacitance generates large (magnetically induced) output currents; and their rigid multilayer structure and inactive surroundings (unaddressed dielectric) inhibit device failure via cracking (albeit at the potential expense of performance).

In 1-cent MLCs that can be mass-produced, ME coupling is easily measured, is a weakly varying function of temperature at RT, and is highly reproducible across field cycles ($V(H)$ is well below the MLC poling threshold) and temperature cycles. Different MLC geometries yield analagous results. MLC sensitivity dV/dH could be significantly improved by appropriate materials selection[5] or by wiring the capacitor plates in series. Direct ME effects in MLCs could be exploited for energy harvesting, and for magnetic-field sensors that do not require electrical power, for example, for underwater, space, health and safety, *in vivo*, teaching or toy applications.

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Competing financial interests

The authors declare competing financial interests: details accompany the full-text HTML version of the paper at www.nature.com/naturematerials

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