

occur in humans, it would mean that we would be able to inherit adaptive immunity to infectious diseases such as polio, which requires rearrangement of DNA in somatic immune cells — the lymphocytes. Although adaptive immunity is not known to be heritable, the inheritance of somatic genetic information in ciliates has long been known to occur⁶. Further support for this form of inheritance comes from studies of DNA deletion in ciliates.

In *Tetrahymena* and *Paramecium*, if a germline sequence is also present in the somatic genome, its deletion is blocked, and the situation is perpetuated in subsequent generations^{7,8}. It is thought that the maternal somatic genome may produce RNA to interfere with the small RNAs (produced from the germline genome) that guide somatic DNA deletion. Some researchers have even postulated that the whole germline genome is transcribed to produce small RNAs to guide DNA deletion, and that the entire somatic genome is transcribed to produce RNA that blocks the deletion of genes destined for the somatic nucleus, thereby establishing sequence specificity for DNA deletion^{3,9}.

Nowacki and colleagues' study¹ gives credence to these ideas. Thus, somatic genomic RNA may occur widely in ciliates to direct DNA rearrangements and affect inheritance; gene unscrambling could be a specific effect of transcription of the somatic genome into RNA. Once the mechanism for gene scrambling has evolved, mutational gene rearrangements in the germ line are tolerated and accumulate,

resulting in an altered genome through evolution.

The study of Nowacki *et al.* ventures into *terra incognita*, as little is known about DNA rearrangement that is guided by a template. The process must be precise enough to recreate functional coding sequences on a genomic scale, and seems to involve local RNA-directed DNA synthesis — the authors found that sequences near rearrangement sites, but not those farther away, were copied from the RNA at high frequencies. There is no reason why similar processes should not occur in other organisms. Altering gene structure can be an effective mechanism for stable differentiation, and RNA is probably the most informative molecule to guide such alterations. The challenge is knowing where to look for it — as the odd and beautiful ciliates have once again reminded us, this is a rich and diverse world. ■

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MATERIALS SCIENCE

Desperately seeking silicon

Cronin B. Vining

Using silicon as a 'thermoelectric' material to convert heat into electricity would be a technological leap forward. But silicon conducts heat so well that nobody thought that could work — until now.

Thermoelectric materials convert heat into electric current, and vice versa. If they could be made more efficient at that conversion, they might be used to suck up waste heat from fossil-fuel combustion processes to make electric current, or as an alternative to photovoltaic cells for converting solar warmth into electricity¹. Silicon, the basic material of semiconductor electronics, is readily available, cheap and has a huge infrastructure and know-how for its production and manipulation. Those are reasons enough to seek a marriage between silicon and thermoelectric properties.

And indeed, silicon is a kind of thermoelectric material — the inefficient kind. In her classic 1947 paper on the efficiency of thermoelectric generators², the Hungarian-American physicist Mária Telkes concluded that “high

efficiency could not be expected” for silicon, because it has such a high thermal conductivity. Silicon conducts heat too well to put it to any use: it is difficult to produce a temperature difference across it that is big enough to generate a useful voltage. Sixty years on, however, two papers in this issue^{3,4} challenge Telkes's assessment. Boukai *et al.* (page 168)³ use silicon nanowires with a rectangular cross-section and Hochbaum *et al.* (page 163)⁴ use round silicon nanowires to achieve thermoelectric efficiencies comparable to those of the best commercial thermoelectric materials.

Thermoelectric efficiency is described in terms of the thermoelectric ‘figure of merit’, ZT , defined as $S^2T/\rho k$. Here, T is the material's temperature, ρ its electrical resistivity, k its thermal conductivity and S is the Seebeck coefficient,

defined as the increase in potential difference per unit temperature rise. Bulk silicon has a ZT of about 0.01 at 300 kelvin (27 °C). For metal wires, the best value at 300 K is about 0.03. Values of 0.7–1.0 are now found in commercially available thermoelectric materials based on bismuth-telluride semiconductors. The first really solid report of much higher figures of merit, up to 2.4, came in 2001, in thin films of a complex semiconductor⁵. But high electrical and thermal losses in these thin films have so far kept them from the commercial big time.

Hochbaum *et al.*⁴ now quote a ZT value of 0.6 for their silicon nanowires. Boukai *et al.*³ cite about 0.4 at 300 K, and around 1 at 200 K — not earth-shattering in comparison with existing materials. But in this context it's worth remembering the old adage about dogs walking on their hind legs: it is not done well, but you are surprised to find it done at all. How exactly does it work?

The answer would seem to be, because size matters. The nanoscale geometries of the silicon wires reduce the thermal conductivity by about 100 times, to a value that is not just low for silicon, but low for any solid. Qualitatively, why this happens is not hard to see. Heat is carried by various particles: phonons, representing lattice vibrations, and charged particles such as electrons and holes (a hole is the absence of an electron, and can be thought of as a kind of positive charge). Introducing obstacles — in the case of the nanowires, edges — reduces that heat flow.

But there remains a modest quantitative problem. Hochbaum *et al.*⁴ point out that no available theory can adequately explain why their values for the thermal conductivity are so very low. Boukai *et al.*³ report even lower values, less than that of silica, whose amorphous structure presents a formidable barrier to heat flow. Admittedly, this won't be the first time that some downward revision to our norms has been required: the concept of ‘minimum thermal conductivity’ has always had a degree of Slack⁶ in it.

Boukai and colleagues' rectangular nanowires were in general smaller than the circular nanowires of Hochbaum and colleagues, with cross-sections of 10 nm by 20 nm and 20 nm by 20 nm, compared with diameters of 20–300 nm for the circular nanowires. This smaller size seems to have led to additional effects. First, it reduces the electrical conductivity of the rectangular nanowires, partly negating the benefit of their decreased thermal conductivity. Second, and more importantly (as this quantity is squared in the expression for the figure of merit), it greatly increases their Seebeck coefficient.

The authors attribute this increase to a phenomenon called phonon drag. Phonons carry heat by thermal diffusion from hot regions to cold. Along the way, they may collide with electrons and holes, losing some of their energy, and in some cases dragging the charge carriers along. The result is a larger Seebeck coefficient, larger thermal voltages and a higher efficiency. For all previously known ‘good’ thermoelectric materials, phonon drag has been a small, even

negligible, effect. Now, engineering phonon drag would seem poised to become a new tool for improving thermoelectric materials.

Although size seems to be the decisive difference between the two sets of results^{3,4}, there are other possibly crucial differences between them: surface roughness, nanowire length and substrate material (in Boukai and colleagues' study³, the nanowire array was suspended above a silicon wafer; in Hochbaum and colleagues' study⁴, it was bedded on silicon dioxide). Sorting out all the science behind these results might take time. We need to develop predictive models, understand the optimum size and doping levels, extend the data to high temperatures, and find out what other materials might show the effects of low thermal conductivity and large phonon drag. And does one really need nanowires at all, or would some

other nanoscale configuration do?

In one stroke (albeit from two directions), the thermoelectric capability of silicon has been improved by a factor of nearly 100. It thus leaps up the scale of thermoelectric materials from 'terrible' to 'not bad'. What happens next is anyone's guess; but I for one am no longer taking bets against silicon's thermoelectric future. ■

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PALAEONTOLOGY

Ancient worms in armour

Jean-Bernard Caron

It requires a quirk of fossilization for the soft parts of an animal to be preserved. Study of such a specimen of the mysterious machaeridians provides these organisms with a well defined evolutionary home.

A 480-million-year-old fossil from Morocco, described by Vinther *et al.* on page 185 of this issue¹, ends a long controversy over a group of enigmatic fossils called the machaeridians. Now convincingly interpreted as primitive segmented (annelid) worms, the extinct machaeridians had a scaly 'armour' of mineralized shell plates over or around a soft body of previously unknown form. This armour represents an adaptation not seen in modern segmented worms, and raises a host of questions about the group's evolution and origins.

Efforts to unravel the machaeridian mystery have faced great challenges. The fossils are common in ancient marine deposits, but are tiny. A complete armour (known as the scleritome) is often smaller than a fingernail. Moreover, the finding of articulated shell plates is extremely rare. No wonder, then, that these animals have been studied by only a handful of scholars since they were first described in 1857 — one of the most comprehensive accounts of the group is a venerable 1926 monograph². Discoveries of rare articulated specimens have added more knowledge on the morphology, mode of growth and function of the scleritome³. But, apart from the recognition of three distinct families of machaeridian (Fig. 1), such studies have not really helped to clarify the wider taxonomic position of the group.

Previous speculations have allied machaeridians to the molluscs, the arthropods or, particularly, the echinoderms. Stefan Bengtsson first convincingly suggested a possible

relationship to the annelids⁴. On the basis of microstructural studies of shell plates⁵, he soundly refuted the echinoderm hypothesis, but unfortunately subsequent indications of a link to the annelids⁶ remained untested. Palaeontologists are sceptics by nature, and most were waiting to see a specimen with the body attached to the plates to be convinced.

Vinther and colleagues' study¹ is based on the oldest known machaeridian scleritome. This remarkable specimen has defied the usual odds of fossil preservation by retaining traces of the elusive soft body. After death, soft body parts typically decompose quickly. Exactly what conditions caused this specimen to be preserved is unknown, but low oxygen levels might have had a role. Admittedly, the specimen will not seem as spectacular to the novice as other, more famous 'soft-bodied' fossils⁷. There is some evidence of disarticulation, and the head is missing, which is a pity because the head section might have provided important morphological information for taxonomy. But the limited disarticulation has allowed some plates to become detached, revealing the body outline of the enigmatic animal underneath (see Fig. 1 of the paper¹ on page 186).

The crucial information lies in the numerous protrusions bearing prominent filaments in bundles along both sides of the animal. The authors interpret these to be parapodia, bearing chaetae, features that are typical of marine bristle worms or polychaetes (literally meaning 'very hairy'). Thus, the fossil machaeridians seem to have



Figure 1 | The machaeridians. Top, a complete machaeridian scleritome from 425-million-year-old deposits in New York state³. Length, 5.4 mm. Bottom, dorsal reconstructions of presumed complete scleritomes (not to scale) showing the diversity of scleritomes within the three families of machaeridians⁹ — running upper to lower, the Lepidocoleidae, Turrilepadidae and Plumulitidae. The fossil specimen (top) is a lepidocoleid; that described by Vinther *et al.*¹ is a plumulitid. All scleritomes are shown with the presumed head to the right. (Top image courtesy of A. Höglström; bottom images courtesy of J. Dziki.)

found a home at last within this larger group. But why some ancient annelids should develop a complex mineralized scleritome, endure for hundreds of millions of years, and then disappear entirely, remain questions for the future.

What are the other implications of this study? Annelids today are thought to be composed of two major groups⁸, the Clitellata (including earthworms and leeches) and the Polychaeta. It is not well understood which of these two groups is the more primitive (basal), and the interrelationships of the polychaetes are still poorly resolved. Whether the machaeridians can help answer these questions is doubtful. Possession of a mineralized scleritome, the presumed ability to roll up, and a fixed number of plates growing by increments are all features of Vinther and colleagues' fossil and of members of the other machaeridian families, but are not present in the modern groups of polychaete³. So perhaps current evidence favours positioning the machaeridians as 'stem-group annelids', that is, not belonging to any modern group of annelids (Fig. 2). On the other hand, identifying machaeridians as primitive polychaetes removes problems arising from their putative assignment to other groups of animals (such as molluscs), and helps constrain broader evolutionary models.

Meanwhile, the deeper origins of the machaeridians have yet to be elucidated. It has been speculated that the roots of this group may lie in the Cambrian explosion, a time of rampant morphological innovation starting about 540 million years ago when mineralized skeletal parts appear suddenly in different groups of animals. Some isolated shells from the Lower