CSEM's

Materials Monthly

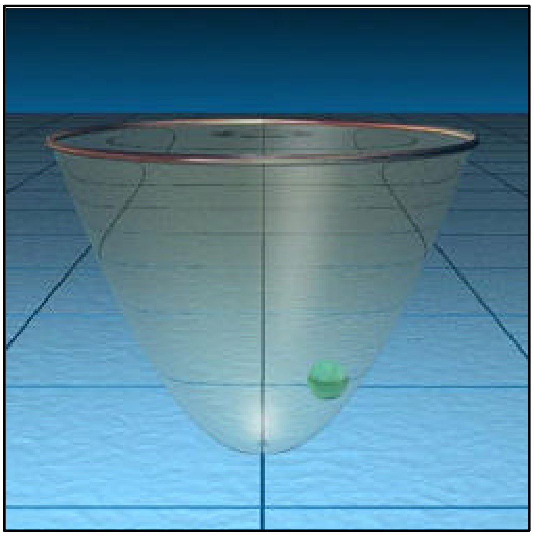
October 2004

Making materials matter

Making light work of tiny forces

Optical tweezers and potential wells

Researchers in the Research School of Chemistry are using optical tweezers to explore microscopic forces in a range of novel investigations.



▲▲ Optical tweezers trap small particles in an imaginary valley or potential well. The further it moves away from the centre, the stronger the force pulling back. (Graphic by David Carberry)

Pushing & pulling with light

It's been known for many years that light could be used to manipulate tiny objects. Some 30 years ago, Arthur Ashkin at the AT&T Bell Labs realised that an unfocussed laser beam could draw objects towards the centre of the beam and propel them in the direction of the propagation. The pulling and pushing power was tiny but sufficient to move very small particles. Laser light refracts through transparent objects in such a way that there is always more light pressure pushing the object towards the focal point than there is pushing it away from it. These forces (radiation pressures) arise from the momentum of the light itself.

This application was developed over the coming years and by the mid 80's optical traps had been refined to such an extent that they were used to trap biological particles. Arthur Ashkin's group at the Bell Laboratories had trapped individual viruses and E-Coli bacteria as early as 1985, and it was in this year that the technique was referred to as optical tweezers.

Since then, optical tweezers have become an important tool of research and the biotechnology industry. They are used to trap and move a wide range of objects such as tiny dielectric spheres, viruses, bacteria, living cells, organelles, small metal particles and even strands of DNA.

In the biological and medicinal sciences optical tweezers are often used to separate different cell types, to manipulate sub-cellular objects without damaging the cell itself and are used in medicinal procedures such as invitro fertilisation.

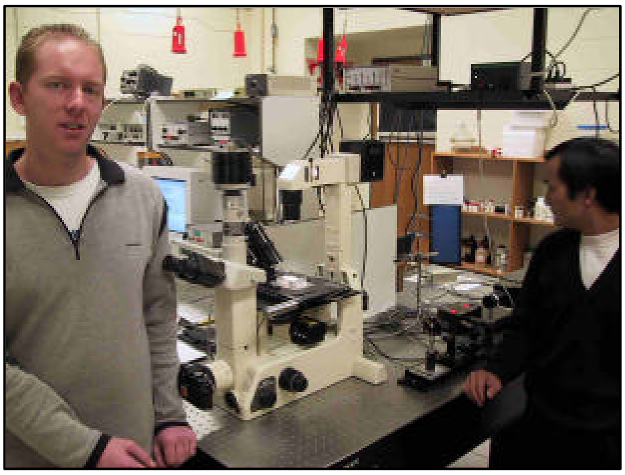
Force measurement

But optical tweezers are much more useful than a simple sorting and micro-manipulation tool. The optical tweezers can also be used as a force-measurement tool. By varying the strength of the laser it is possible to exert a force on a particle ranging between a thousandth of a pico Newton up to 100 pico Newtons (a pico = 10^{-12}). This in turn can be used in single-molecule research, for example the stretching of single polymer chains, or to examine the orbital angular momentum transfer properties of lasers.

David Carberry is a doctoral student in the Polymers and Soft Condensed Matter group at the Research School of Chemistry. He uses a modified optical tweezers facility to carry out exactly these types of investigations.

"The original version of the optical tweezers we're using came to us as a device that could separate biological cells and other transparent particulates, it had no force measurement capabilities," David explains. "We've created this capacity by adding several components, the most important being a quadrant photodiode. This addition enables us to measure the position of a particle within the optical trap to within 15

(Continued on page 2)



▲▲ David Carberry (left) with Dr Genmiao Wang and the optical tweezers apparatus. Dr Wang performed the first experimental test of the Fluctuation Theorem.

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Light work of tiny forces

(Continued from page 1)

nm. By knowing the distance the particle has moved away from the focal point of laser beam, and the strength of the laser beam that has created the optical trap, it's possible to calculate the strength of the force that moved the particle."

"Think of the optical trap as being potential well," says David. "And the particle being trapped as a ball trapped at the bottom of this potential well. The stronger the laser beam, the steeper the sides of the well, and the greater the force required to move the particle away from the centre of the well. The weaker the beam, the more gently inclined the walls of the well, and the easier it is to force the ball to move away.

The distance the ball moves away from the trap is proportional to the size of the force pushing against the ball."

The particles in these experiments are small latex sphere or beads suspended in water. The beads are 6 microns across.

"To trap a particle, a suspension of balls and water is moved around on the microscope stage until a ball is located" says David." "The laser is switched on and the ball moves into the focal plane. To test that it is trapped, a current is produced that would normally move the particle away if there were nothing holding it in place."

Unravelling molecules

So, having developed a device capable of measuring exquisitely small forces acting on a latex ball, what is it used for?

"Our group has been using the apparatus in a range of investigations," says David. "My particular interest lies in two areas: first, we're seeking to determine the force required to unwind a strand of DNA in different solvent conditions, and second, we are testing the theory on the thermodynamics of small systems, an area being developed by Professor Denis Evans with his work on the Fluctuation Theorem."

What's the interest in pulling apart long polymers like DNA?

"Traditionally, polymer science has relied upon bulk measurements using techniques such as neutron/light scattering and rheology to characterise melts and solutions of polymers and biopolymers," explains Dr Edith Sevick, Head of the Polymers and Soft Condensed Matter group. "These measurements provide useful information on an ensemble of molecules, but they are limited in that they do not detail individual molecules. Today, research at the forefront of chemistry and biology is at the single molecule level: examples include DNA for molecular storage and retrieval of biological information, as well as single protein molecules which act as chemo-mechanical motors.

"Optical tweezers has advanced the study of single polymer chains and biopolymers by allowing one to image and directly manipulate chains using pico Newton scale forces on length scales ranging from Ångstroms to microns. These experimental techniques have inspired new molecular-based theories and simulations, allowing combined experimental, simulation, and theoretical approaches to these single-chain problems."

In other words, you can learn a lot about a functionality of a long chain molecule by recording the tension in the chain as you stretch it out. However, stretching a molecule is a lot easier said than done.

"Basically, the process involves applying a special coat to the latex bead so the end of a DNA chain latches onto it," says David. "The bead is held in place by an optical trap and a current is then generated in the surrounding solution so the molecule gets spread out.

"Another bead is brought into contact with the trailing mass of tangled molecule. It's covered in a different coat that will latch on to the other end of the molecule. Attaching the second bead is the tricky bit. However, if we can achieve that, the second bead is then attached to the end of a micropipette by suction and the second bead is slowly pulled away from the first bead.

"The tension in the unravelling DNA molecule is reflected by the distance the first bead is pulled away from the centre of the optical trap. The further the first bead moves, the greater the pulling force being applied to it and the greater the tension in the DNA molecule."

The thermodynamics of small systems

The work on thermodynamics of small systems uses a variation of the system. The latex bead is dragged through the solution using the smallest of forces. Most of the time the bead will go exactly where you drag it. However, every once in a while it will actually move in front of where you're going due to collisions with molecules in the surrounding solution. This is an outcome that seemingly violates the 2nd Law of Thermodynamics.

"However, this observation is fully explained by the Fluctuation Theorem," says David. "This theory was devised by a team led by Professor Denis Evans, Dean of RSC, to explain why small systems operating over small time frames don't obey the 2nd law. It's a very significant refinement on how the world works because it suggests that nano-machines do not operate as simple scaled-down versions of larger machines.

"Most importantly to our work, our apparatus carried out the world's first real life demonstration of a prediction coming out of the Fluctuation Theorem. We're currently working to further refine this work."

Optical tweezers have played an enormous role in manipulating objects and systems over small scales. By using them to measure tiny forces, they have now opened up whole new fields of molecular research.

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Optical tweezers

may the force be with you

Lasers can be dangerous: they have the potential to cut, burn and destroy. However, there is also a kinder, gentler side to them. Set up in an appropriate way they can act like a tiny pair of tweezers, trapping and manipulating microscopic particles without another object physically touching them.

Light has radiation pressure. When light is absorbed, reflected or refracted by a dielectric material, tiny forces on the order of pico Newtons are generated. For reference, several milliwatts of power corresponding to a bright laser beam gives only a few pico Newtons (pN) of force. However, a force of 10 pN is sufficient to pull a bacterium such as *E Coli* through water ten times faster than it can swim. The force is proportional to the power of the laser.

Optical tweezers work by means of the gradient force of light. A sharp focal point is created using a laser, and when a small particle comes into contact with the focus it remains trapped. The particle is pulled towards the more intense light because it has a greater index of refraction than the surrounding medium, and momentum must be conserved.

Butterfly tables

▲▲ Julie Kennett with her prototype table made from blackwood.

Wood is a wonderful material for crafting furniture. It's strong, easy to shape, relatively light, and each piece has its own unique character. However, it also comes with limitations, one of which is its tendency to shrink and expand depending on the ambient humidity.

This is the main reason why so much care needs to be taken when putting together table tops (and other furniture). Also, it helps to ensure that they last a lot longer. The individual pieces, however, need to be well cured and closely matched to each other so they don't move too much relative to the other pieces. It's also why table tops need to be thick and solid, so there's a large joining area where the individual pieces are fixed together. Small movements in one piece are held firm preventing distortions over the table top.

Because of these limitations, fast grown plantation timbers or mismatched timbers are avoided when it comes to putting together a quality table top because the boards usually respond differently in the manner in which they shrink and expand.

However, that may be about to change thanks to a smart new design being trialled by Julie Kennett, a Visual Arts / Science student based at the Wood Workshop in the ANU School of Arts. Rather than rigidly fixing the boards of the table top to each other, they are held together (and apart) by wooden butterfly joints that can move with the wooden planks as they expand and shrink over time. Individual boards no longer store up tension because the adjacent board can expand or shrink without pushing all pulling directly on its neighbour.

The butterfly joints are not glued but rather held in place by hemp cordage, and the entire table top is held up by a series of wood buttons that complement the table design by also allowing movement of the planks as they shrink and expand.

It's a functional and stylish solution to an age old problem. The butterfly joints not only allow for movement, they also give the table top an elegant and unique appearance.

"In this prototype model I've used blackwood," says Julie Kennett. "It's a relatively fast-growing wattle and a pioneer Australian tree species. It was chosen because of the various values that it has for many cultures and communities in Australia. Unfortunately, due to its fast-growing nature it is considered one of the softer of the hardwoods and usually wouldn't be considered in table tops, however it works well in this design."

Julie's technique also means the planks don't have to be so thick because they don't need to be physically fixed to each other.

"This design doesn't require thick, premium-grade timbers which are becoming more and more uncommon." she explains. "The hope is we can explore the potential of a range of Australian timbers that previously have never been considered for this type of use, and construct furniture that corresponds to these timber qualities and the Australian climate. This includes plantation timbers and recycled timbers. It raises a number of exciting possibilities."

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▲▲ The butterflyjoints are held in place with twine recessed into the wood.

Blackwood timber

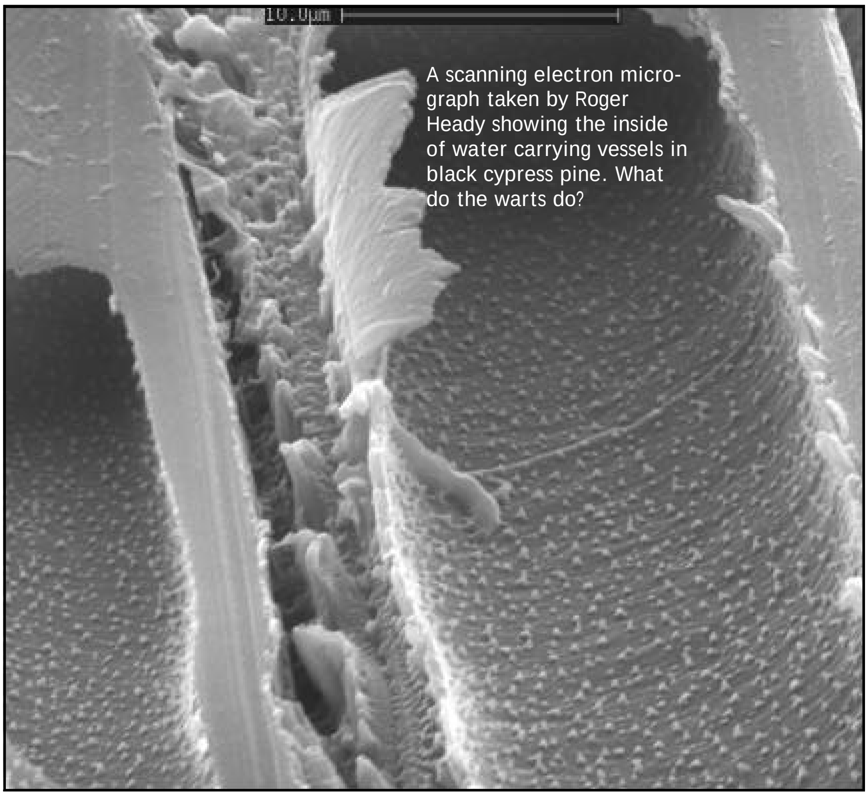
The timber of blackwood, *Acacia melanoxylon*, display attractive shades of brown, and are often quite dark. These colours are the source of its scientific name. Melanoxylon comes from the Greek 'melanos' black and 'xylon' wood. The timber has a strong surface lustre, and is often beautifully figured with stripes and fiddleback patterns. Blackwood is prized for cabinet work, panelling, inlays, bent work and staves. It also possesses good acoustic qualities and is sought after for violin backs.

It's natural distribution of the wattle (pictured below) is from southern Queensland along the New South Wales coastal ranges, across Victoria and south- eastern Australia and Tasmania. This fine, hard timber was also widely used by Aborigines being made into spear-throwers, boomerangs, clubs and shields in parts of Victoria. People also soaked the bark in water to bathe painful joints and the inner bark was used to make string.

Warts and all

"What do the warts do?" asked Dr Roger Heady when his scanning electron microscope studies of water vessels* in cypress pines revealed the linings were covered in tiny wart-like growths. It was this question and those images that proved an irresistible hook to Dr Mika Kohonen when he chose to study water transport in trees.

"We take it for granted but the task of transporting water up trees is a truly amazing process," says Mika, a research fellow working with Dr Vince Craig in the Department of Applied Maths, RSPhysSE. "How do trees manage to transport water to heights of up to 100 metres without using a pump? It's done through a remarkable and complex network of capillaries interconnected by safety valves that can isolate a section of the network when the water column cavitates or breaks during times of drought or heat stress. That much is well known. What's not really understood is the mechanism by which these sections become refilled with water later on.



A scanning electron micrograph taken by Roger Heady showing the inside of water carrying vessels in black cypress pine. What do the warts do?

"I'm examining the interaction of water with the lining of these water vessels. Surprisingly, little is known about what's happening on a microscopic scale at this interface."

Which is where the 'mystery of the warts' takes on a special significance because it's been observed that many trees living in dry and variable climates have warty outgrowths on the lining of their water vessels.

"There have been a number of hypotheses put forward to explain what the warts do," says Mika. "One proposal is that they increase the flow rate. However, in that they decrease the cross section of the vessel and increase the turbulence of the flow this doesn't seem likely. Another theory is that they catch bubbles rising up with the water. To do this they would need to be hydrophobic (water repelling) however our studies suggest they are hydrophilic (water loving) so this explanation also seems unlikely.

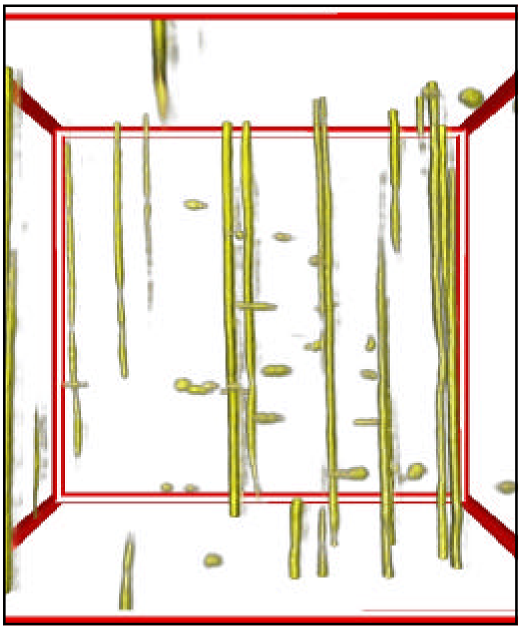
Mika Kohonen with a sample of cypress pine.

"Our investigations, using a variety of techniques including light and electron microscopy, and 3D computer tomography, suggest the warts actually increase the 'wettability' of the lining of the water vessels. This is important because when a column of water breaks and fills with air during a time of water stress, the task of refilling that vessel at a later time when water is plentiful is made much easier if the lining of the vessel is still wet. This possibility is increased if the lining is highly wettable. Even if it dries out, the warts would assist in water reentering the empty vessel and moving over the lining."

Studies such as Mika's are far from academic. The field of microfluidics, solutions passing through networks of capillaries, is a big growth area at the moment as micro and nano technologies are reducing whole lab systems down to the size of glass slides. Maintaining and directing fluid flow down tiny tubes is central to these new technologies. Understanding the transport of water in the capillary network of trees might possibly provide important solutions to a number of emerging fluid-flow problems.

More info: Mika.Kohonen@rsphy1.anu.edu.au

* The term 'water vessel' is used through out this article as it best describes the function of these plant water pipes. Strictly speaking, however, these pipes are called tracheids in gymnosperms (such as pines) and the term 'vessels' refers specifically to the pipes in angiosperms.



The image here is a tomogram (3D image) showing the inside of water carrying vessels that have cavitated and are now filled with air. (The vessels carrying water and the vessels themselves have been rendered invisible in this image.) ▶▶

Engineering a better wheel

With the rise of wheelchair sports and the growing popularity of the Paralympics there's been a big demand for improved designs of all aspects of the wheelchair, but especially in the wheel. Usually, improvements are based on a trial-and-error approach, however one enterprising young Engineering Honours student has developed a methodology which provides a means of comparing different wheelchair designs. What's more, he's used this approach to see if he can improve the design of the wheels used by Louise Sauvage, one of Australia's leading Paralympic gold medallists.

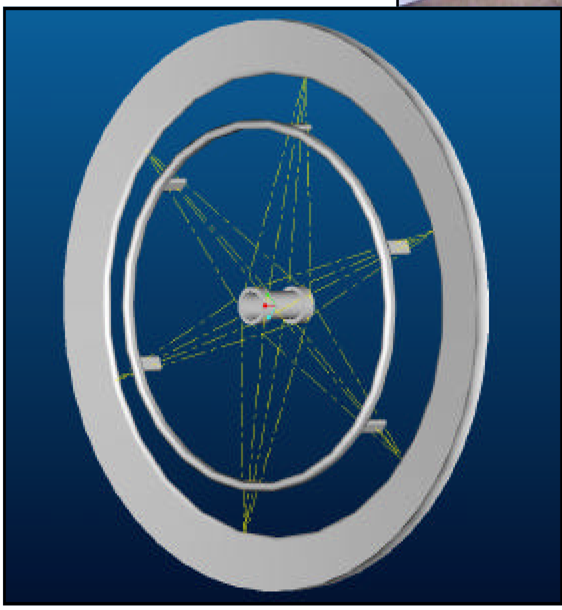
Aaron Watters is the student in question and he was asked by Stuart Andrews, the designer of Louise's wheels, to see if he could improve on the design. Using finite element analysis, Aaron was able to model the existing wheel design and determine which of its elements might be improved. He found that the pushrim, a disc of fibre composite over the hub of the wheel, was probably over engineered. So, he set about finding design alternatives.

A number of design solutions were analysed and compared on the basis of weight, rotational moment of inertia, side profile and wheel stiffness. From this it was decided that a thin pushrim attached via spokes to the rim and the hub in a tangential spoking pattern would offer the best solution.

This new design has reduced the wheel mass by 49%, rotational moment of inertia by 41% and reduced cross sectional area by 95% (thereby decreasing cross wind resistance). However, first versions of this new design lost some degree of the stiffness in the original design. Further refinement on the fibre orientation and thickness of the pushrim composite have largely compensated for this problem.

Aaron believes he now has a significantly better design for a competitive wheelchair racing wheel. Indeed, his improvements may well provide a winning edge in future competitions. The next challenge is to take to the design through a real wheel, something he is currently discussing with designer Stuart Andrews.

More info: Aaron Watters <u3304058@anu.edu.au>



▲▲ Aaron with the design that has taken Louise Sauvage (pictured below) through to many victories. His new design (left) looks like providing significant improvements on this original design.

Physics for the Nation Jan 31 - Feb 4, 2005, ANU

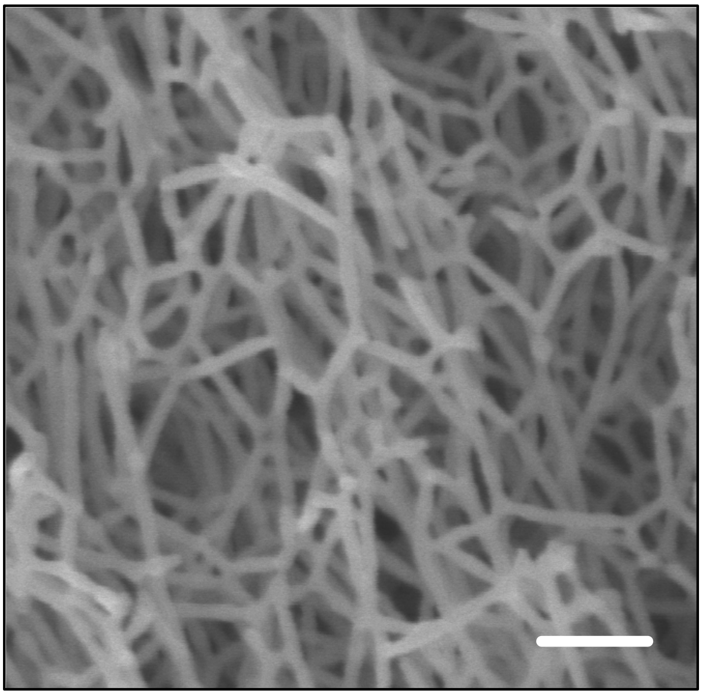
Do you have any interest in any of the following groups?

- AIP (Atomic and Molecular Physics & Quantum Chemistry Group; Nuclear & Particle Physics Group; Physics Education Group; Women in Physics Group)
- Astronomical Society of Australia
- Australasian Society for General Relativity & Gravitation
- Australian Acoustical Society
- Australian Institute of Nuclear Science & Engineering
- Australian Meteorological and Oceanographic Society
- Australian Optical Society
- Australian Society of Exploration Geophysicists
- Australian Synchrotron Research Program
- Condensed Matter and Materials "Wagga" Meeting
- Photonics Institute Pty Ltd
- Science Educators' Association of the ACT
- Solar-Terrestrial and Space Physics
- Specialist Group on Solid Earth Geophysics, Geological Society of Australia
- Vacuum Society of Australia

If you do you should be coming to the 16th Biennial Congress of the Australian Institute of Physics being run in Canberra early next year because they're all involved. This is likely to be the largest gathering of physicists in Australia since the 1988 Bicentennial Congress, and perhaps the largest ever. Can you afford not to be there?

More info: http://aipcongress2005.anu.edu.au/index.php

Pick the pic



Nanosponge

The image on the left looks like the inside of a sponge or some type of algal growth. However, as soon as you know the white space bar in the bottom right hand corner is only 100 nanometres long you realise this structure is a bit smaller than your average sponge—by a factor of around a hundred million!

The tubes that make up this structure are around 15 nm in cross section and are made of gallium antimonide (GaSb). They were produced by bombarding a solid mass of the semiconductor GaSb with gallium ions.

Normally, when you implant ions into a semiconductor they become embedded in the semiconductor crystal lattice. Implant high energy ions into GaSb, however, and you also produce little holes or pores. Continue to implant more ions and the holes grow to create voids that eventually link up to leave rod like structures as are shown here.

These structures were produced by Dr Susie Kluth from the Department of Electronic Materials Engineering (RSPSE). They arose out of studies on the amorphisation of crystalline structures using implanted ions. The investigation has turned up some truly stunning shapes and surprises (all of which we'll explore in the November issue of *Materials Monthly*.)

More info: Susan.Kluth@anu.edu.au

Relativity Rules

Want to earn an easy $42,000? All you have to do is explain Einstein's theory of relativity to a lay person in a five-minute interactive multimedia presentation. The Pirelli Group have laid down this Relativity Challenge to anyone in the world, as part of the International Year of Physics. Entries close on 31 March 2005 and the 25 000 Euro cheque will be handed over in a ceremony in Rome that Northern summer.

Check it out at www.pirelliaward.com/einstein.html

PIRELLI RELATIVITY CHALLENGE

Young Einstein ▶▶

And while we're on the topic of Einstein, brace yourself for a deluge of Einstein-related anecdotes, images, quotes and trivia because 2005 was chosen as the International Year of Physics because it marks 100 years since Albert Einstein rewrote the rules of the universe. For those of you who want to bone up on a little Einstein science, history and philosophy, check out the American Institute of Physics website on the great man.

Go to www.aip.org/history/einstein/

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