In summary, we have demonstrated that selective Si diffusion into GaAs can be achieved by the selective modification of the GaAs surface using an ion bombardment. This allows for a simple maskless selective diffusion technology in GaAs.

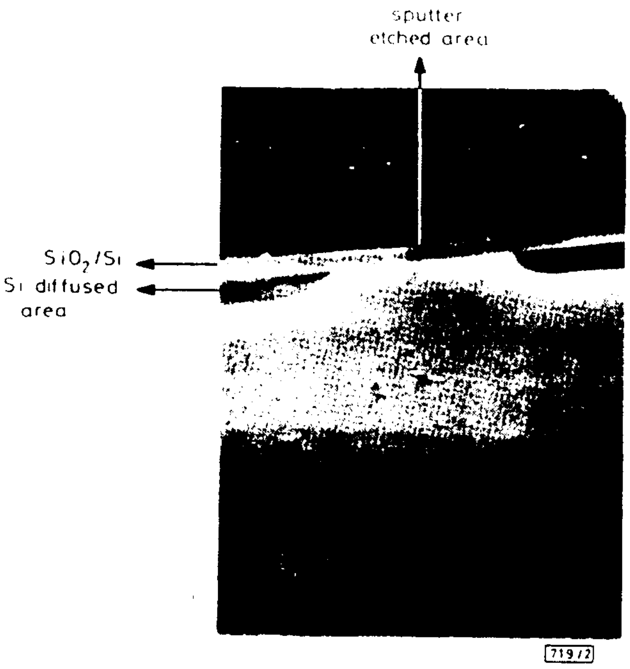

Fig. 2 *SEM photograph of stained cross-section showing selectively diffused pn junction as obtained with selective sputter etch*

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References

1 MEEHAN, K., BROWN, J. M., HOLONYAK, N., BURNHAM, R. D., PAOLI, T. L., and STREIFER, W.: 'Stripe geometry AlGaAs–GaAs quantum well heterostructure lasers defined by impurity-induced disordering', *Appl. Phys. Lett.*, 1984, **44**, pp. 700–702

2 GREINER, M. E., and GIBBONS, J. F.: 'Diffusion and electrical properties of silicon doped gallium arsenide', *J. Appl. Phys.*, 1985, **57**, pp. 5181–5187

3 GREINER, M. E., and GIBBONS, J. F.: 'Diffusion of silicon in gallium arsenide using rapid thermal processing: experiment and model', *Appl. Phys. Lett.*, 1984, **44**, pp. 750–752

4 OMURA, E., WU, X. S., VAWTER, G. A., COLDRÉN, L., HU, E., and MERZ, J. L.: 'Closed tube diffusion of silicon in GaAs from sputtered silicon film', *Electron. Lett.*, 1986, **22**, pp. 496–498

5 CHANG, C. C., CITRIN, P. H., and SCHWARTZ, B.: 'Chemical preparation of GaAs surfaces and their characterization by Auger electron and X-ray photoemission spectroscopies', *J. Vac. Sci. Technol.*, 1977, **14**, pp. 943–952

SINGLE-MODE TAPERS AS 'FIBRE FUSE' DAMAGE CIRCUIT-BREAKERS

Indexing terms: Optical fibres, Optical communications, Optical transmission

The 'fibre fuse' thermal damage effect can destroy kilometres of fibre at relatively modest laser powers. A low-loss tapered region strategically placed in a single-mode fibre can act as a thermal circuit breaker, thereby halting the damage propagation and protecting the fibre 'upstream' from the taper.

Introduction: The 'fibre fuse' thermal shock-wave is a catastrophic damage mechanism which can occur in optical fibres carrying modest average power densities.[1–3] The effect can be initiated simply by heating a section of the fibre (a match flame is sufficient) while laser light is propagating through it: other initiating processes include the act of cleaving the fibre, contact of the fibre output end with absorbing materials,[1] or evanescent wave interaction with a metal film.[2] Although apparently different, all of these methods result in local heating of the fibre. A sharp increase in absorption occurs when the fibre is heated above 1000°C, leading to a runaway thermal effect which, provided the laser power is sufficient, continues until the core melts. At this point the absorption abruptly rises to a much higher level and the thermal shock-wave (the 'fibre fuse') is created, locally heating the core glass to such a temperature that permanent damage ensues. Once initiated, the shock wave (which is visible as a bright spot of side-scattered light) propagates back along the fibre towards the light source, leaving the fibre core permanently damaged and unable to guide light.

The damage mechanism has been observed both with a continuous wave (CW) Ar^+ laser[3] operating on all visible lines (452–514 nm) and a CW mode-locked Nd : YAG laser[1,2] operating at 1·06 μm; it is a purely thermal effect and appears to be power rather than wavelength dependent. Typically, a laser power of ~300 mW is sufficient for the initiation and propagation of the thermal shock-wave in a single-mode fibre. As this power threshold is relatively low, many fibre-based systems are at risk from this damage mechanism, and the destruction of over a kilometre of fibre has been reported.[2] Some kind of damage-limiting component would therefore be desirable in such a system.

The fibre fuse effect is known to be power-density dependent,[3] and so it was decided to investigate the application of a taper beam expander[4] as a thermal circuit breaker. It was found that the taper did, indeed, stop the propagation of the fuse effect. Interestingly, however, the fuse effect was found to terminate not at a point where the beam suffered an absolute expansion,[5] but only where the beam expanded relative to the core radius. This fact suggests that as well as being a power-density effect, the fibre fuse also depends on the dopant (Ge) present in the core.

Experiment: A section of coating was stripped off each of the fibres to be tested, and a low-loss taper fabricated using a conventional burner technique. An Ar^+ laser, operating on all visible lines to maximise power, was launched into the test fibre. The coating was stripped off a small section of fibre on the far side of the taper, and the stripped section was subsequently heated with a match flame in order to initiate the fuse. Fuse propagation could be observed by looking at the bright spot of side-scattered light. The resultant damage in both tapered and untapered sections of fibre was investigated using an optical microscope.

One of the fibres tested was single-moded at 450 nm (cut-off 410 nm). In this fibre, the fuse propagated in the usual fashion but stopped at the point in the taper where the fibre diameter was reduced by ~8%, leaving the rest of the fibre undamaged (Fig. 1). The damage pattern was seen to change slightly at the start of the taper. A double-mode fibre was also tested; the tapered region had a very similar effect on fuse propagation, again halting it shortly after the start of the taper (after ~4% reduction in diameter). With a highly multi-mode fibre, however, the fuse was able to propagate right through a tapered section, melting it in the process with a 'cracking' sound.

Discussion: Although the single-mode fibre taper is well known as a beam expander,[4] spot size enlargement only occurs beyond the point where the local V-value is about[5] 2. In the single-mode fibre experiment described above, thermal damage was observed to stop after the fibre diameter had been reduced by only 8% in the taper. Calculations of the fundamental-mode spot size[4] show that the field at this point in the taper had not in fact expanded relative to the field in the untapered fibre, and that the light intensity between both points was therefore virtually unchanged. However, the fraction of modal power within the core had reduced as a result of the decrease in the core diameter. This indicates that the material composition of the fibre core is an important factor in determining fuse propagation: indeed, we have observed this type of thermal damage only in germanosilicate-core fibres, and there is evidence that the dark appearance of damaged core material is at least partly due to germanium suboxides.[2] The fibre taper therefore serves to reduce the fraction of the guided power affected by Ge-doped regions, so the conditions for damage propagation become less favourable. This process continues until, after the 8% diameter reduction, shock-wave propagation can no longer be sustained.

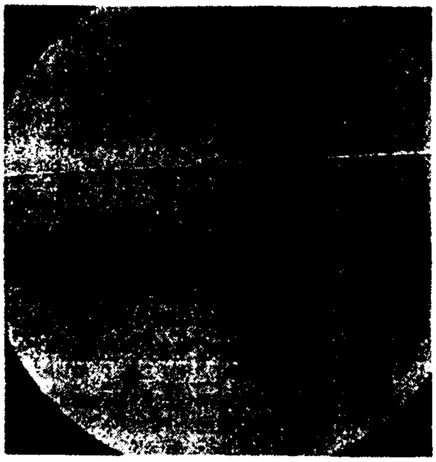
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Fig. 1 *Termination of damage track in single-mode Ge-doped fibre taper*

A taper in a double-mode fibre acts in a very similar way. Most if not all of the power in the LP_{11} second-order mode was lost in the taper, so the power in the fibre 'downstream' from the taper was mainly in the fundamental mode. Therefore, for the purposes of the fibre fuse shock-wave (which propagates in the opposite direction to the optical field), the taper in the double-mode fibre acted exactly like a taper in a single-mode fibre. At the point where the damage stopped, calculations show that the optical field had actually contracted slightly compared to the field in the untapered fibre. The proportion of the power within the core was however reduced, as it was for the single-mode fibre.

Tapering a highly multimode fibre produces a very different result. Although tapering will cut off the highest order modes, a considerable number of modes will still propagate through the taper. These modes remain well-confined within the core, so the optical field will be compressed in the taper waist and the fraction of power within the core will be little changed. Not only does this enable the thermal shock-wave to continue propagating, but the higher light intensity in the taper leads to much higher peak temperatures which, as we observed, can cause the whole fibre to melt.

Conclusion: The 'fibre fuse' thermal shock-wave damage mechanism in single-mode optical fibres can be halted by a section of tapered fibre. Fibre tapers therefore act as low-loss thermal damage circuit breakers, and can be employed as such to protect, or at least to limit damage in, single-mode fibre systems operated at high powers. For example, low-loss tapers could be inserted into a fibre line at regular intervals: if the fibre fuse was accidentally initiated at any point, only a short length of fibre would need to be replaced, rather than the whole system upstream of the initiation point.

The slight extent of tapering necessary to stop damage propagation indicates that the shock-wave mechanism is very material dependent, and as an experimental result has two significant practical consequences. Firstly, a section of fibre tapered to the extent that the fundamental mode expands to become a cladding mode[4] should act as a damage circuit breaker for optical powers many times the damage threshold of the fibre; in the experiment described above, there was a great deal of 'spare' field expansion in the taper. Secondly, slightly-tapered sections could be used to protect fibre with a 'depressed-cladding' index profile, which can only be tapered to a limited extent with low loss.[6] This includes important classes of fibre, such as dispersion-flattened and high-birefringence fibres.

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References

1 KASHYAP, R.: 'Self-propelled self-focusing damage in optical fibres'. Proceedings of Tenth International Conference on Lasers (Society for Optical and Quantum Electronics, McLean, USA, 1987)

2 KASHYAP, R., and BLOW, K.: 'Observation of catastrophic self-propelled self-focusing in optical fibres', *Electron. Lett.*, 1988, **24**, pp. 47–49

3 HAND, D. P., and RUSSELL, P. ST. J.: 'Solitary thermal shock-waves and optical damage in optical fibres: the fibre fuse', *Opt. Lett.*, 1988, **13**, pp. 767–769

4 JEDRZEJEWSKI, K. P., MARTINEZ, F., MINELLY, J. D., HUSSEY, C. D., PAYNE, F. P.: 'Tapered-beam expander for single-mode optical fibre gap devices', *Electron. Lett.*, 1986, **22**, pp. 105–106

5 LOVE, J. D.: 'Spot size adiabaticity and diffraction in tapered fibres', *ibid.*, 1987, **23**, pp. 993–994

6 BOUCOUVALAS, A. C., and GEORGIOU, G.: 'Tapering of single mode optical fibres'. Technical digest of IOOC-ECOC, 1985, 1, pp. 575–578

MICROWAVE PERFORMANCE OF PSEUDOMORPHIC RESONANT-TUNNELLING HOT ELECTRON TRANSISTORS AT 77K

Indexing terms: Semiconductor devices and materials, Transistors, Tunnelling

The letter describes the first 77 K microwave measurements for resonant-tunnelling hot electron transistors (RHETs) fabricated using GaInAs/AlInAs pseudomorphic heterostructures. A collector current peak-to-valley ratio of 10 is obtained with a peak collector current density of 2×10^5 A/cm^2. A current gain cut-off frequency f_T of 63 GHz and a maximum oscillation frequency f_{max} of 44 GHz are measured at 77 K with an emitter current density of $1{\cdot}1 \times 10^5$ A/cm^2.

Introduction: In 1985, we proposed and fabricated a three-terminal resonant-tunnelling device, named RHET, which used a GaAs/AlGaAs heterostructure.[1] We demonstrated various attractive features of RHETs for memory and/or logic applications.[2] In 1987, we demonstrated that lattice matched RHETs exhibit improved current gain and collector current peak-to-valley ratio.[3] However, there have been no reports on RHET microwave performance at 77 K. This paper reports the first 77 K microwave measurements for RHETs.

Experiments and results: Fig. 1 shows the band diagram of the RHET that we fabricated for this study. The emitter resonant-tunnelling barriers (RTBs) consists of 41 Å-thick $Ga_{0{\cdot}47}In_{0{\cdot}53}As$ sandwiched between 25·5 Å-thick $Al_{0{\cdot}65}In_{0{\cdot}35}As$ pseudomorphic barriers. This RTB exhibits a high emitter conductance and high current peak-to-valley ratio. It uses an $(Al_{0{\cdot}5}Ga_{0{\cdot}5})_{0{\cdot}48}In_{0{\cdot}52}As$ collector barrier to increase the current gain. The base width is 300 Å and the carrier concentration is 1×10^{18}/cm^3. All the epitaxial layers