Near-Infrared Channel Waveguides Formed by Electron-Beam Irradiation of Silica Layers on Silicon Substrates

R. R. A. Symns, T. J. Tate, and J. J. Lewandowski

Abstract—Results are presented for channel guides formed by electron beam irradiation of silica layers formed on Si substrates by plasma-enhanced chemical vapor deposition. Electroplating is shown to be a simple method of fabricating the required surface mask. Optical insertion loss measurements performed at 1.525 \( \mu \)m wavelength show a strong dependence on the irradiation mask width, charge dose, and electron energy, and parameters for low propagation and coupling loss are identified. Optimum propagation losses are 0.4 dB/cm (TE), 0.75 dB/cm (TM). Spectral loss measurements are also presented for as-deposited and thermally annealed material, and it is shown that beneficial results are obtained by annealing before irradiation. The stability of irradiation-induced changes is also described.

I. INTRODUCTION

SILICA-ON-SILICON is now well established as a materials system for integrated optics [1]–[3]. Processes for forming buried topographic guides have been developed for different dopants, based on a variety of glass deposition methods, and extremely low propagation loss can be obtained [4], [5]. However, since the formation of a buried ridge typically requires two glass deposition steps, a reactive ion etching step, a reflow step, and a burial step, there is still a need to investigate simpler methods of fabrication. Two methods are currently under investigation: laser irradiation and electron beam irradiation. Both are still in their infancy but offer a number of potential advantages. Only a single layer is required to form a buried channel guide, and the surface is left flat enough for further processing. However, questions concerning propagation loss and guide stability have yet to be fully addressed.

To form a guide by laser irradiation, a focused high-power laser beam is scanned mechanically over the silica layer. The radiation will be absorbed if the laser wavelength is close to one of the mid-IR absorption bands; CO\textsubscript{2} lasers (\( \lambda = 10.6 \) \( \mu \)m) are therefore appropriate. If the material is sufficiently porous, local heating can cause densification and a rise in refractive index. Most of the effort has therefore concentrated on porous sol-gel glasses, which consolidate at a low temperature (although tuning of devices made in flame hydrolysis glass has also been reported [6]). Planar and strip guides have been formed by laser irradiation, but published propagation losses are high [7], [8]. Little work has been performed on single-mode channel guides, and neither suitable direct-write systems nor reliable surface masking methods have been reported.

Waveguide formation by electron beam irradiation is analogous; a high power electron beam is scanned over the silica layer [9]. However, the changes on silica caused by electron irradiation are more complicated than those induced by heating. Known effects include the generation of \( E' \), peroxy radical and nonbridging oxygen-hole (NBOH) centre defects. However, irradiation may also cause the liberation of common molecular species such as \( H_2 \), \( H_2O \), and \( O_2 \), which diffuse and react with the defect sites [10], [11]. As a result, local compaction and expansion (accompanied by an increase or decrease in refractive index) may both occur, depending on the initial degree of purity of the silica [12], [13]. In multicomponent glasses (e.g., soda-lime glass), further chemical migration (e.g., sodium/calcium migration) has also been suggested as a mechanism for refractive index changes [14].

Irradiation-induced compaction has been used for channel guide formation in bulk silica and silica-on-silicon [15], [16]. Similarly, irradiation-induced expansion has been used to form channel guides in silicon oxynitride bilayers by depressing the refractive index on either side of a guiding strip [17]. This method is less satisfactory; however, it has recently been found that the behavior of some silica-based materials exhibiting expansion can be almost exactly reversed by a short thermal anneal prior to irradiation, thus allowing direct waveguide fabrication [18]. The annealing must be performed carefully, however, since a lengthy or high-temperature anneal appears to eliminate any irradiation sensitivity.

Flood irradiation can obviously be used to fabricate planar guides [16]. More recently, it has been used to tune the coupling strength of directional couplers based on topographic guides [19]. However, the fabrication of any channel guide circuit requires localized irradiation. Direct writing has been used [14], but because of the insensitivity of silica-based materials, a high-power beam is required to minimize writing time. Since the quality of such a beam is invariably low, channel guides are mostly fabricated by flood irradiation through a surface mask [15]–[18]. Suitable electron-stopping masks have been formed by reactive ion etching a thick...
(> 0.7 \mu m) Au layer [15], [18]. While it is possible to implement the required process, it has in practice been found to be relatively expensive and difficult.

Propagation losses of irradiation-induced guides are still high compared to those of topographic guides. The lowest figure quoted is 0.3 dB/cm, obtained in a 14-\mu m-thick layer of SiO_2 formed on Si by LETI, France, using plasma-enhanced chemical vapor deposition (PECVD) [15], [16]. However, since the test wavelength (0.633 \mu m) was unrealistic, this result does not represent practical performance. At 1.525 \mu m, the best result to date is 1.7 dB/cm, obtained in 12-\mu m-thick PECVD SiO_2 on Si supplied by BNR Europe Ltd., England, after the response reversal described above [18]. This figure is clearly less useful; furthermore, significant differential was observed between the TE and TM performance.

Because low-loss topographic guides have been fabricated in both the materials described above, it is reasonable to eliminate optical scattering as the major contributor to high propagation loss. Instead, we can identify substrate loss (which also accounts for the larger part of any TE/TM loss differential). Substrate loss is significant in irradiation-induced guides because the weak refractive index changes obtained are often insufficient to confine the optical mode far enough away from the substrate. Naturally, the problem is more acute at infrared wavelengths because of the increased mode size.

In addition, OH and other hydrogen-related absorption peaks appear in many silica materials at near-IR wavelengths. As previously mentioned, these cannot be eliminated easily by annealing prior to irradiation without entirely reducing the irradiation sensitivity. Unfortunately, the obvious alternative—postirradiation annealing—also removes irradiation-induced changes when performed under the conditions required to dehydrate the silica fully, namely, for long times and at high temperatures [16], [18].

Some of these aspects can undoubtedly be addressed by careful adjustment of the process parameters. However, any demonstration that electron beam irradiation can be used as a practical method of waveguide fabrication must show that low insertion loss can be obtained. Consequently, any strategy for optimization of propagation loss through minimization of substrate and OH absorption losses will only be of value if it can simultaneously deliver usefully low fiber coupling loss.

In this paper, we show that many of the difficulties described above can be overcome. First, we show that electroplating may be used as a simple, cheap, and reliable method of surface mask fabrication. Second, from measurements of optical insertion loss at 1.525 \mu m wavelength, we identify fabrication parameter choices—nominal guide width, irradiation charge dose, and electron energy—for optimum propagation and coupling loss. In the process, we show that TE propagation and coupling losses can be reduced to \approx 0.4 dB/cm and 0.2 dB/facet, respectively. TM losses are slightly higher. Third, we present spectral loss measurements for waveguides formed in both as-deposited material and annealed material, and show that beneficial results are obtained by annealing before irradiation. Finally, we describe the effect of annealing on the stability of irradiation-induced changes.

![Fig. 1. Masking process for waveguide fabrication by electron beam irradiation of silica.](image)

II. METHOD

A. Silica-on-Silicon Material

All experiments were performed on material supplied by LETI, France. This consisted of 16-\mu m-thick layers of PECVD SiO_2, with a refractive index of 1.472, on 4\" (100) Si wafers [20].

B. Masking

The electron-stopping surface mask required for localized irradiation at the energies used (25–40 keV) can be provided by a thick, patterned Au layer. The original mask fabrication processes [15], [17] were based on subtractive patterning of a metal multilayer. The first layer was a Cr adhesion layer, which also acted to discharge any surface charge during irradiation. The second was an Au layer, which was patterned by reactive ion etching, using a third layer as an etch mask. However, the required Au thickness (> 0.7 \mu m) caused difficulties in both deposition and etching.

We have therefore developed an alternative process based on additive patterning. This eliminates the need for vacuum deposition and etching of thick Au layers, and is cheap, fast, and reliable. Starting with a suitable SiO_2 layer on Si substrate [Fig. 1(a)], a 100 \AA Cr adhesion layer and a 100 \AA Ni electroplating seed layer are deposited by evaporation [Fig. 1(b)]. Shipley S1400-27 photoresist is then spin-coated and patterned with the waveguide mask to leave resist only in the guide regions [Fig. 1(c)]. Au is then electroplated around this pattern to the required thickness in a commercial gold potassium cyanide bath [21] [Fig. 1(d)]. The resist is then washed away in acetone, and the exposed Ni layer removed by wet etching [Fig. 1(e)], leaving the Cr to act as a discharge layer [Fig. 1(f)].

Unstressed Au films are obtained by electroplating at low current densities (\approx 7 A/m^2). Under these conditions, we find that the \approx 0.7 \mu m Au required for device fabrication can be plated in \approx 1.5 h with a cathodic efficiency of 60% and a thickness uniformity of \pm 5% over an area of 3 cm \times 4 cm. Using this process, there is no difficulty in fabricating masks for guide widths as small as 4 \mu m.
C. Irradiation

All irradiations were performed using a modified Camscan 5-20 DV SFM, fitted with a column extension and a mumetal screen to allow a 4" × 4" area to be irradiated by beam deflection under control by a PC running a simple CAD system. Alignment of the sample and adjustment of the beam parameters is performed with the instrument in SEM mode. The maximum beam current is 1 mA. However, irradiations are typically performed at 0.1 mA beam current, so that a sample of standard area 3 cm × 4 cm can receive a charge dose of, e.g., 0.5 C/cm² in 3 × 4 × 0.5/(0.1 × 10⁻³ × 3600) ≈ 17 h. The instrument is fitted with a substrate table that can be cooled to 20°C during irradiation, and heated to 90°C while the sample is loaded and unloaded (to prevent condensation).

D. Optical Measurements

The irradiated features consisted of straight guide sections of widths 4, 5, 6, and 7 μm. Guides were formed in arrays of 8 off of each width for each set of irradiation parameters (charge dose, electron energy, etc.) used. After removal of the surface mask by wet etching, chips of standard length 4 cm were then cleaved to yield standard waveguide arrays of length 32 mm ± 1 mm.

Insertion losses were found at 1.525 μm wavelength by comparison of fiber-fiber and fiber-device-fiber transmission, using standard 8/125 μm single-mode fiber and the apparatus of Fig. 2. A broad-band fused coupler provided a reference to allow compensation for variations in laser output, and a λ/2 plate was used to rotate the polarization for measurement of TE and TM modes. Coupling and propagation losses were separated by the cutback method. The spectral variation of insertion loss was measured using a computer-controlled spectrometer fitted with a tungsten halogen lamp. Unless otherwise stated, tests were performed with an overlay of oil of refractive index 1.43.

III. RESULTS

A. Response of Silica Material to Electron Beam Irradiation

Electron beam irradiation of LETI PECVD silica has previously been shown to result in an increase in refractive index [15], [16]. For example, Fig. 3 shows the variation of the TE mode index change Δn = n_{eff} − n_{sub} with charge dose, for planar guides formed by irradiation at 25 keV electron energy. This follows a saturating law, with a peak change of Δn_{max} ≈ 7.5 × 10⁻³. The rise in index is accompanied by a compaction of the irradiated volume. As with other materials, measurement of the step height between irradiated and unirradiated areas indicates that the compaction varies linearly with index change [17], [18]. The saturation charge dose was on the order of 0.2 C/cm². It should be noted that this value differs by a factor of 5 from previous results [15]–[17] of 1 C/cm², due to a calibration fault in our coulomb meter. This implies an increase in sensitivity to irradiation by the same factor.

B. Variation of Channel Guide Insertion Loss with Charge Dose

Although a range of nominal mask widths was available for channel waveguide fabrication, the best performance was obtained from the largest guide width. The results that follow are therefore mainly for 7 μm nominal width. Similarly, results are for single-mode guides unless otherwise stated.

Previously, channel guides have been formed using charge doses of ≈ 0.2 C/cm². However, there are advantages in operating further into the saturation region of the material response. This results in an approximately step-index guide profile, with a greater cross-sectional area of high index change, and hence increased modal confinement. Fig. 3 also shows the variation of fiber-device-fiber insertion loss with charge dose for 7-μm-wide guides formed by irradiation using 25 keV electron energy. The insertion loss is extremely high for low doses, but reduces quickly as the dose rises to ≈ 0.2 C/cm². However, useful improvements can be obtained using higher doses, and TE insertion losses of 1.6 dB were routinely obtained at charge doses greater than ≈ 0.5 C/cm². There was a significant difference in TE and TM insertion losses. However, this also reduced as the dose increased, and the corresponding TM loss at high doses was 2.5 dB.

The optimum insertion losses can be separated into coupling losses of 0.2 dB (TE), 0.15 dB (TM), and propagation losses of 0.4 dB/cm (TE) and 0.75 dB/cm (TM). While the major factor contributing to propagation loss is substrate absorption, there is a small contribution from surface scattering, which also reduced as the dose increased. Without an index-matching overlay, TE and TM insertion losses typically rose by ≈ 0.05
Fig. 4. Insertion loss versus electron energy for 7-μm-wide single-mode channel guides formed by irradiation at 0.26 and 0.42 C/cm² charge doses.

dB and ≈ 0.3 dB, respectively (for guides formed using high doses). With an overlay, insertion losses were uniform from guide-to-guide to ≈ ±0.1 dB.

C. Variation of Channel Guide Insertion Loss with Electron Energy

Fig. 4 shows the variation in insertion loss with electron energy at two different charge doses. At 0.26 C/cm², it was found that minimum losses were achieved at 30 keV energy. However, the insertion loss was found to be very sensitive to the electron energy, rising rapidly at smaller and larger energies. In each case, this is attributed to a rise in substrate absorption (at lower energy, due to the reduced size of the guide, and at higher energy, due to the increased depth of the guide). At 0.42 C/cm² charge dose (i.e., further into the saturation region), the sensitivity to energy was enormously reduced. At higher doses still, the best performance was obtained at 25 keV energy.

D. Variation of Insertion Loss with Guide Width

Fig. 5 shows the variation of insertion loss with guide width for guides formed using low (0.26 C/cm²) and high (0.9 C/cm²) charge doses and 25 keV energy. At the lower dose, the loss is very sensitive to guide width, increasing rapidly for smaller guides (which are presumably close to cutoff). At the higher dose, sensitivity to width has mostly disappeared, indicating that the modes are now well confined. However, there is still a slight variation for the TM mode. This is attributable to a rise in propagation loss (0.75 dB/cm for 7 μm width, 0.9 dB/cm for 4 μm width) for smaller guides, due to increased substrate absorption.

E. Spectral Variation of Insertion Loss

Fig. 6 shows the spectral variation of insertion loss for 7-μm-wide guides formed by irradiation at 25 keV electron energy and doses ranging from 0.1 to 0.74 C/cm². Two separate contributions to loss may be identified. First, at low doses, the loss rises steadily as the wavelength increases. This feature is again ascribed to substrate loss, which increases as modes approach cutoff. At high doses, this sensitivity is largely eliminated. Second, large absorption peaks at 1.39 and 1.5 μm wavelength may clearly be seen. These features are characteristic of PECVD SiO₂ containing hydrogen. It is assumed that the former corresponds to the first harmonic of the Si-OH bond and the latter to either the second harmonic of the Si–H bond or the first harmonic of the N–H bond [4]. At 1.39 μm wavelength, the effect is to introduce additional propagation loss (i.e., over and above substrate and scattering losses) of 1.4 dB/cm. At 1.5 μm, the corresponding figure is 2.4 dB/cm.

Fig. 7 shows the variation of the excess loss at 1.39 and 1.5 μm wavelength with dose. These results (which are somewhat inaccurate due to the difficulty in isolating extrinsic absorption from other losses) show a reduction in excess loss with dose that correlates strongly with the corresponding increase in refractive index. This behavior suggests that one effect of irradiation may be to librate hydrogen, which may then diffuse to the SiO₂ surface and escape. However, it is not the only effect.

F. Stability of Irradiation-Induced Changes

As mentioned earlier, the index changes caused by irradiation are accompanied by compaction. Consequently, channel guides may be located quite simply by observation of the accompanying surface depression. For example, Fig. 8 shows the surface profile at a 7-μm-wide guide formed using 0.9 C/cm² charge dose, 25 keV electron energy. This shows a considerable depression (≈ 1000 Å) at the guide center, which falls off gradually on either side. The extent of the strain field is much larger than the nominal guide width (the half-width is ≈ 5 μm, while the full width is ≈ 25 μm).
Changes in compaction caused by thermal annealing can be used to estimate the stability of irradiation-induced effects. Previously, stability has been assessed by annealing for a fixed time at different temperatures (isochronal annealing), and the reduction in irradiation-induced effects observed at a particular temperature has been ascribed to a process occurring only at or above a threshold temperature [16]. However, it appears that thermal removal of irradiation-induced effects is a simple Arrhenius process. This is revealed most clearly by the alternative experiment of annealing at a fixed temperature for different times (isothermal annealing).

For example, Fig. 9 shows the variation in the compaction (normalized to its initial value $C_0$) at the edge of a planar guide, for LETI SiO$_2$ annealed at different temperatures. In each case, the compaction falls roughly exponentially with time, with a faster decrease at higher temperature. This encourages the hypothesis that the removal of irradiation-induced changes follows the law

$$C/C_0 = \Delta n/\Delta n_0 = \exp(-t/\tau).$$

(1)

Here $\tau$ is a time constant dependent on temperature. If removal is caused by a single thermally activated process with activation energy $E_a$, we would expect $1/\tau$ (the process rate) to follow

$$1/\tau = 1/\tau_0 \exp(-E_a/kT)$$

(2)

where $T$ is the absolute temperature; this implies a linear variation of $\ln(1/\tau)$ with $1/T$.

By fitting exponential functions to the results of Fig. 9, $1/\tau$ can be found at different temperatures. The exponentials are shown superimposed on Fig. 9, and Fig. 10 shows the variation of $\ln(1/\tau)$ with $1/T$ found from them. Since the data are reasonably consistent with (1) and (2), the hypothesis of a single Arrhenius process appears realistic. From the intercept and slope of the line in Fig. 10, $E_a$ and $1/\tau_0$ can be estimated as 1.63 eV and 14,500 s$^{-1}$, respectively.

Using these values, the likely lifetime of irradiated waveguides and the effect of further processing can be estimated. Fig. 11 shows theoretical curves for normalized compaction of LETI SiO$_2$ versus process temperature, for times in the range 0.3–30,000 h. These curves are very similar to results obtained experimentally in isochronal annealing experiments [16], and suggest that indefinite operation at room temperature or further PECVD processing at 350°C for a limited time are possible.

G. Reduction of Hydrogen Contamination

In tophographic guides, hydrogen-induced absorption peaks of the type shown in Fig. 6 are conventionally eliminated...
by annealing at a high temperature [4]. However, due to the thermal sensitivity of irradiation-induced changes, this approach is inappropriate here. For example, a channel guide formed by the electron beam process was annealed for 5 min at 750°C in O₂. Even after such a short, low-temperature anneal, insertion losses at 1.525 μm wavelength rose from 2.9 dB (TE) and 7.2 dB (TM) to 4.3 dB (TE) and 9.3 dB (TM), presumably because of increased substrate absorption caused by a slight increase in guide ∆n.

An alternative approach to posteriorannealing is preirradiation annealing. Elsewhere, it has been shown that materials having a positive irradiation-induced index change may survive even high-temperature thermal preprocessing with only a small change in their irradiation sensitivity [18]. In LETI material, low-loss guides have been successfully formed following 20 min anneal at 1150°C; a temperature far in excess of that cited above. Fig. 6 also shows the spectral response obtained using thermal preprocessing; clearly, the absorption peaks at 1.39 μm (0.6 dB/cm) and 1.5 μm (1.3 dB/cm) are considerably lower than those obtained without preprocessing.

Further improvements (0.45 dB/cm at 1.39 μm, 0.9 dB/cm at 1.5 μm) were achieved after annealing at 1200°C. Increased substrate losses were observed, suggesting a reduction in the achievable refractive index change. Nonetheless, these results encourage the belief that low, spectrally flat losses may be obtained merely by using thicker silica layers.

IV. DISCUSSION

We have shown that near-infrared channel waveguides with acceptable losses may be formed by electron-beam irradiation of silica-on-silicon when the material is well driven into saturation. Two main performance limitations were observed. The first is substrate absorption; for near-IR guides, this is very significant, but the solution is clearly to use a thicker silica layer. The second is extrinsic absorption due to hydrogen contamination. Good progress was made in reducing the hydrogen concentration by thermal annealing prior to irradiation, but further work is clearly needed to determine the performance that may ultimately be obtained.

We now turn to two important questions that have been ignored in favor of our main theme of waveguide technology development: what is the mechanism for the change in refractive index that occurs on irradiation, and how are the changes removed during any subsequent thermal annealing step? Unfortunately, both of these questions are difficult to answer; a brief survey of the literature shows that the range of possibilities is large, and that few firm conclusions have been reached. At present, our own experiments are also inconclusive, so all we can do is summarize the difficulties.

One possible mechanisms for the induced refractive index change is the liberation of molecular species, which merely diffuse through the silica lattice and escape—for example, we have already mentioned that hydrogen is apparently liberated on irradiation. However, the variations in hydrogen concentration thus induced cannot be the major cause of the changes observed. The evidence was presented in Section III-G, where a substantial reduction of hydrogen contamination was achieved by thermal annealing prior to irradiation, without changing the level of substrate absorption (and hence without reducing the index change). An alternative mechanism—the relaxation of strained bonds—is also unlikely, given the degree of annealing to which the material was subjected. The most likely mechanism is therefore the creation of defects from precursors that are already present in the PECVD silica, and that are themselves stable enough to survive a thermal annealing step before irradiation.

As mentioned in the Introduction, there are three main types of paramagnetic defects in SiO₂: E’, peroxy radical, and NBOH center defects. Their investigation has mainly been performed using electron spin resonance (ESR), and the results thus obtained have recently been reviewed by Warren et al. [22]. The E’ defect is an unpaired electron (•) localized in the sp³ orbital of a silicon atom bonded to three oxygen atoms (O₃≡Si•). This introduces an ultraviolet absorption band or color center at 5.77 eV (215 nm), and a corresponding refractive index change at visible and IR wavelengths. However, nine slight variations of the generic E’ defect have been identified, each occurring in different forms of silica. Its precursor is assumed to be the oxygen vacancy (O₃≡Si—Si≡O₂), although another possibility is a strained cyclic trosloxane (three-membered ring). The peroxy radical has an unpaired electron localized over two oxygen atoms (O₃≡Si—O—O); this introduces absorption at 7.63 eV (163 nm) and its precursor is the oxygen surplus (O₃≡Si—O—O—Si≡O₂). Finally, the NBOH center has an unpaired electron localized in the pₓ orbital of oxygen (O≡Si—O’), which introduces visible absorption bands at 2.00 eV (630 nm) and 1.63 eV (760 nm); its most likely precursor is the hydroxyl group (O≡Si—OH). These defects can all be created during irradiation by neutrons, electrons, x-rays, X-rays, and UV light. However, the relative proportions created depend on the material. For example, it appears that E’ defects are always generated, but that peroxy radicals are present in greater proportions in dry silica (< 5 ppm OH) while NBOH centers dominate in wet silica.

Identification of the defect responsible for the observed effects requires a correlation between either volumetric or refractive index changes and the defect density. In principle, the defect density may be determined either by optical spectroscopy or by ESR. However, because the induced changes occur in a waveguide geometry, we have found that it is very difficult to separate the various contributions to loss over the required range of dose in spectroscopic experiments. In particular, the waveguide confinement is poor at low dose, so that the modal overlap with the irradiated region is low while substrate losses are high. Our current efforts are therefore now being directed to ESR experiments.

Annealing of the defects is thought to take place through reactions with molecular species that diffuse from interstitial sites. Confusingly, the reactions can involve defect transformations; for example, an E’’ defect may react with O₂ to form a peroxy radical [23]. Alternatively, new products may be formed—for example, an E’ defect may react with hydrogen to form silicon hydride [24]. Because diffusion and reaction steps are both involved, the kinetics of annealing
may be complicated. In addition, variations in the density of the silica can cause variations in the diffusion coefficient of the molecular species concerned. As a result, the activation energies associated with particular annealing reactions are not unique [23], and it would be rash to identify the reaction involved here merely from the value of 1.63 eV derived in Section III-F.

Because of these difficulties, we are adopting the following strategy. First, we are attempting to improve waveguide performance through the use of thick silica layers, which is dehydrated as far as possible by thermal annealing prior to irradiation. These experiments should at least allow the thermal stability of the defect precursors to be identified, and show whether waveguides may eventually be formed in material that is free of OH losses. However, the dehydration process should also limit the range of defect creation reactions that can occur, and hopefully allow the most important defect to be identified by ESR. Finally, dehydration should limit the range of possible defect annealing reactions, allowing the reaction to be identified unambiguously and waveguide stability to be quantified.

ACKNOWLEDGMENT

The authors gratefully acknowledge useful discussions with the program partners (BT Labs, BNR Europe Ltd., Oxford Plasma Technology Ltd., and Liverpool University). The help and encouragement of Prof. M. Green is also gratefully acknowledged.

REFERENCES


R. R. A. Sym, photograph and biography unavailable at time of publication.

T. J. Tate, photograph and biography unavailable at time of publication.

J. J. Lewandowski, photograph and biography unavailable at time of publication.