Ion Beam Manipulation of the photorefractive properties of SBN planar waveguides.

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Abstract :

Photorefractive planar waveguides have been fabricated in cerium doped Strontium Barium Niobate ($Sr_xBa_{1-x}Nb_2O_6$: SBN) single crystals by ion beam implantation. The losses measured were as low as 0.1 dB cm^{-1} and 7.0dB cm^{-1} for the TM and TE modes respectively. Subsequent two beam coupling experiments performed on the waveguides showed that, unlike $BaTiO_3$ and $KNbO_3$ waveguides formed by ion beam implantation, the two-beam coupling gain direction did not reverse. The response time had also been reduced by two orders of magnitude.

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The advantage of fabricating waveguides in optical materials is that due to the beam confining properties inherent to a waveguide, a high light intensity is preserved throughout the guide. In a photorefractive material, this intensity enhancement is particularly advantageous as the photorefractive response time is dependent on the intensity. Hence, for a given input power, a substantial decrease in the response time will be observed. A further advantage is that using a waveguide geometry provides compatibility with other integrated optical devices. Photorefractive materials such as $BaTiO_3$, $KNbO_3$ and SBN all have large electro-optic coefficients (r_{42} = 1640 pm V^{-1}, r_{42} = 380 pm V^{-1} and r_{33} = 1340 pm V^{-1} for $BaTiO_3$,KNbO3 and SBN respectively) resulting in strong photorefractive responses. SBN is an interesting material as its electro-optic coefficient compares favourably with $BaTiO_3$ but it does not suffer the 6-9°C phase transition like $BaTiO_3$.

A variety of methods has been used to fabricate both planar and channel waveguides in SBN previously: sulphur diffusion[2], ion beam implantation[3], strain techniques[4] and electro-optically[5]; the first two producing planar guides and the latter two, channel. In the case of the sulphur diffused guides, losses were high and although the guides were still found to be electro-optic, no photorefractivity was observed. In the case of the ion implanted guides, again no photorefractivity was observed, although since the guide was implanted onto the z-face of the material, the photorefractive effect would be inherently more difficult to detect. However, for ion implanted $BaTiO_3$ and $KNbO_3$ waveguides, a strong photorefractive effect *was* observed[6,7]. In order to determine whether a guide is photorefractive, two beam coupling is usually performed with two mutually coherent extraordinarily polarised beams interfering within the waveguide. The interesting feature of ion implanted $BaTiO_3$ and $KNbO_3$ waveguides was that the gain direction in the waveguide was opposite to that in the bulk suggesting that the predominant charge carrier had changed (in both cases from hole to electron). In both cases the authors suggested that a form of chemical reduction was occurring within the waveguide layer, induced by the ion implantation process. Since the predominant charge carrier in SBN is the electron, prior to any ion implantation experiments, it was thought that no gain reversal in SBN guides would be seen as the implant has a reducing effect. Furthermore, it was thought possible to dramatically reduce the response time within the guides as the theoretical results of Klein[8] predict that this occurs as the crystal is chemically reduced. We discuss our result on SBN waveguides in comparison with this theory.

To fabricate the waveguides, the crystals were mounted in a vacuum chamber and bombarded with 2.0MeV H^{-} ions which were directed nominally perpendicular to the surface (i.e. parallel to the x-axis) of the crystal. The ions penetrate the surface layer of the crystal initially interacting electronically with the crystal lattice which produces little or no damage to the crystal. However, once the ions slow down, they undergo nuclear collisions forming a damaged layer which has a refractive index lower than that of the bulk. Both SBN:75 and SBN:61 crystals have been studied here, which have Curie temperatures of 57°C and 75°C respectively. Unlike the procedure adopted in ref. 3. the current used was kept deliberately low (≈0.05μA) in order not to heat unduly the surface of the crystal as this may cause adverse effects in the waveguide layer. If the waveguide layer is heated beyond the Curie point it depoles and no photorefractive effect is subsequently observed. This may explain why no report of photorefractivity was observed in ref. 3 as the current used was six times higher than the one reported here. All our implantations were carried out at room temperature with initial doses of 2×10^{15} ions cm^{-2} in the SBN:61 and 1×10^{16} ions cm^{-2}

in the SBN:75. In the SBN:61, two further implants of 2×10^{15} ions cm^{-2} were subsequently performed into the existing guide and a further implant of 1×10^{16} ions cm^{-2} into the SBN:75. In order to determine the resulting guide depth, the crystals were examined under the microscope. The waveguide can be seen clearly by looking at the z-face as the implanted region is appears darker than the bulk crystal. Using 2.0MeV H^{+} ions, the depth was measured to be $(30 \pm 1)\mu m$. After each implant losses were measured and the photorefractive response time was measured via two beam coupling.

To measure the losses of the waveguides, the crystals were precision end polished in order to obtain maximum coupling efficiency. Light was then launched into the waveguide using a $\times4$ objective and collected at the exit of the waveguide by a $\times10$ objective which imaged the light from the waveguide onto a calibrated power meter. All losses were measured at 647nm due to the high transmission of SBN at this wavelength. Table 1 shows the losses observed for the SBN:61 waveguide and Table 2 , those of the SBN:75 guide for different doses. It is interesting to observe how the losses of both the TM mode and the TE mode for the SBN:61 increase dramatically as the implantation dose increases. The losses incurred in the SBN:75 showed the same trend but to a lesser extent. This may be attributable to increasing conductivity in the waveguide layer but ,as yet, no clear explanation is available. The losses obtained for the 1×10^{16} ions cm^{-2} dose are believed to be the lowest measured in any SBN planar waveguide. For other ion implanted waveguides such as $LiNbO_3$, waveguide losses have been reduced by annealing at 200°C [9] . This was not attempted in the SBN guides because of the low Curie temperatures as mentioned earlier. It was also found that the damaged layer of the waveguide has a dramatically increased conductivity, making crystal repoling difficult (for each crystal it was found that a maximum electric field of $\approx 100V\ cm^{-1}$ could be applied while the usual poling field is around $1.5kV\ cm^{-1}$).

To determine whether the guides were photorefractive, a series of two beam coupling experiments were carried out. For the SBN:61, all the fabricated guides had retained their photorefractive properties. However, for SBN:75, only the waveguide with the 1×10^{16} ions cm^{-2} dose still showed photorefractive behaviour. The beam coupling experiments showed that the gain direction within the waveguides was the same as that of the bulk, while, as stated previously, in both $BaTiO_3$ and $KNbO_3$ waveguides, the gain direction had reversed. This non gain reversal within the SBN waveguides implies that, as predicted, electrons remain the predominant charge carrier after the implantation whereas gain reversal would indicate a change in predominant charge carrier from hole to electron or vice versa. The photorefractive response time was also measured for the bulk and the three SBN:61 waveguides implanted at different doses as a function of incident irradiance (Figure 1). It can be seen clearly how the response time decreases as the implantation does increases. Although a faster time would be expected in a waveguide compared to the bulk due to the beam confinement, if the response times are compared at a common value of irradiance (unlike the results presented in ref. 6), the reduction in the response time with ion implantation dose is evident. If the response times are compared at the same intensity for the different implantation doses (Figure 2) again, it is apparent that the implantation is having a profound effect on the intrinsic photorefractive properties. In summary, the two important experimental results we have observed in SBN were the non gain reversal in two beam coupling and the decrease in the response time.

Klein et al.[8] has showed how the impurity ion oxidation state ratio affects the photorefractive gain and response time. Figure 3 (plotted using the parameters for $BaTiO_3$, but still relevant to SBN) shows that the gain and response time vary as the donor/acceptor ratio, or reduction ratio, (X / X^-) increases. Looking at the plot for the gain, Γ, against X / X^- , as the crystal is reduced $(X^- + e^- \rightarrow X)$ the predominant charge carrier changes from hole to electron. In both $BaTiO_3$ and $KNbO_3$ the gain direction reversed, implying a change in predominant charge carrier from hole to electron. However, since SBN is initially an electron conductor the reduction process would not change the dominant carrier i.e. it remains an electron conductor. One possible scenario is that during the implantation process, the H^- ions (and He^+ ions for $KNbO_3$) disrupt the lattice creating oxygen vacancies. In order to compensate for this charge imbalance, the reduction ratio changes, chemically reducing the crystal. It is this reducing effect that causes the predominant carrier to change, and hence the gain direction reverses in $BaTiO_3$ and $KNbO_3$. To explain the decrease in the response time with increasing implantation doses. we have to revert to the plot in Figure 3 showing how the response time varies as the reduction ratio increases. Once the crystal has been reduced such that it is in the electron conducting regime (as it is initially with SBN), as the reduction ratio increases, the response time decreases. As the implantation dose increases, the amount of reduction required to restore the charge balance will increase hence the reduction ratio will increase. It is this behaviour we suggest which causes the reduction in response time measured. In the case of the SBN:75 waveguide with an implantation dose of 2×10^{16} ions cm^{-2}; no photorefractive effect was observed. There are two possible explanations for this. Firstly, it is possible that such a high dose damages the waveguide layer of the crystal such that it is no longer photorefractive, or secondly, it may be that the reduction ratio has been increased to such an extent, that the photorefractive gain is negligible (as predicted in Figure 2 with the plot of Γ against X / X^{-}). These reduction effects have been observed in other photorefractive materials (BaTiO3 and LiNbO3) when crystals have been heated in reducing atmospheres [8,10].

From Figure 2, it can be seen how the response time has been reduced by over two orders of magnitude in the waveguides. This is an interesting result as, combined with the reduction in response time due to the waveguiding properties, photorefractive waveguide devices with considerably faster response times than their bulk counterparts can be designed. A further advantage of this reduction effect is that the photorefractive properties can be manipulated, with accuracy, by ion beam implantation.

In conclusion, we have produced planar waveguides in SBN:61 and SBN:75 by implanting bulk crystals with H^{+} ions. The losses measured were as low as 0.1dB for the TM mode which we believe to be lowest loss reported in SBN waveguides to date. The resulting guides were shown to have preserved their photorefractive properties with the gain direction in the waveguide the same as that of the bulk. The photorefractive response time was reduced by two orders of magnitude by increasing the implantation dose due to the chemically reducing properties of the implant. This is believed to be the first report of the photorefractive effect in SBN waveguides, and their optimisation through ion beam implantation. Future work will involve looking at the effect of sequential ion implantations on losses as currently it is unknown if the source of the increasing losses is due to the dose or the sequential nature of the implant.

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Table 1. Losses in ion implanted SBN:61 (assuming coupling efficiency of 80%)

Table 2. Losses in ion implanted SBN:75 (assuming coupling efficiency of 80%)

Figure 1. Response time versus irradiance for bulk and waveguide SBN:61

Figure 2. Response time versus ion implantation dose in SBN:61

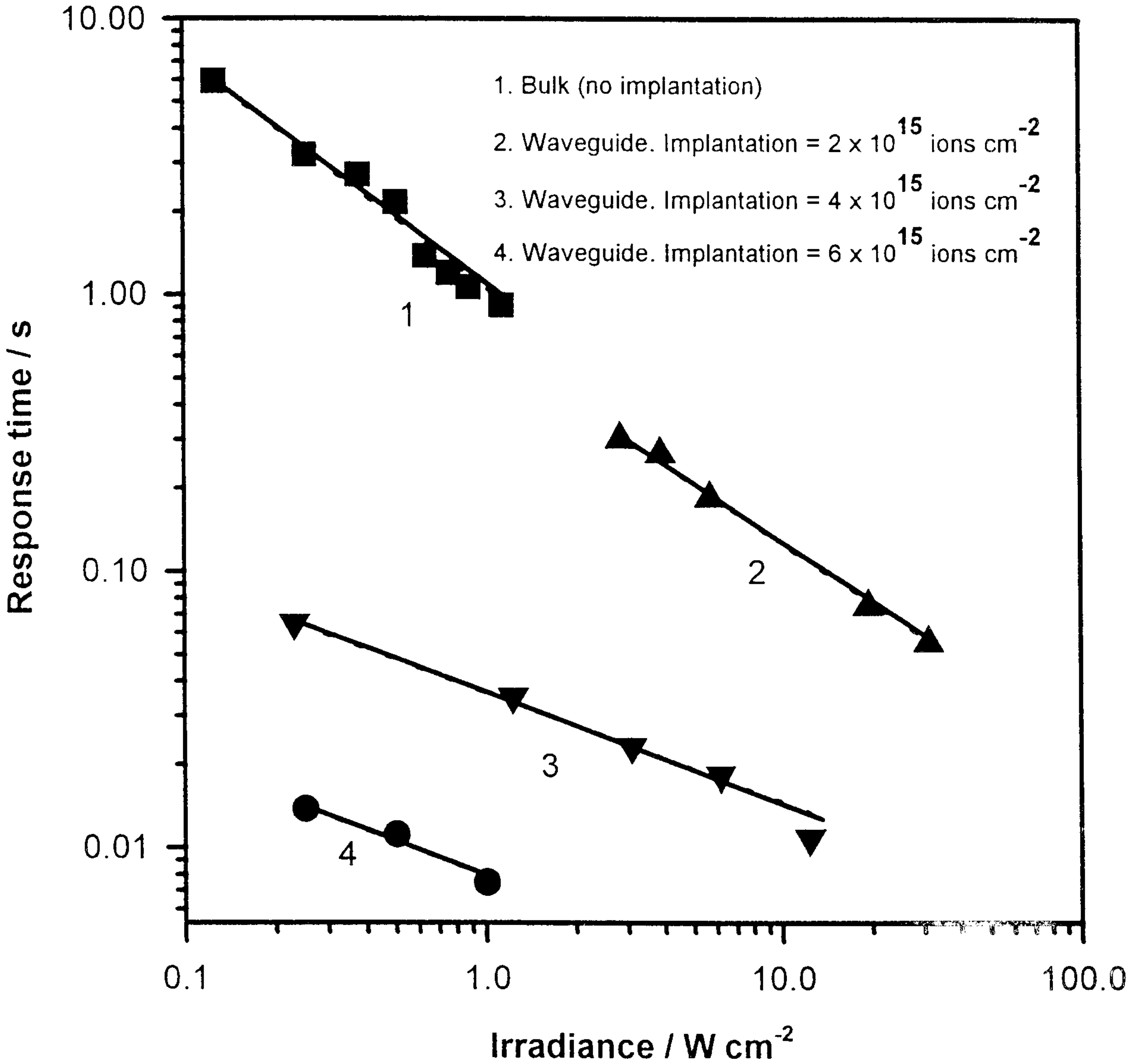
Figure 3. Response time and beam coupling gain in $BaTiO_3$ (after ref.. 8)

Dose / ions cm^{-2}	TM loss / dB cm^{-1}	TE loss / dB cm^{-1}
2×10^{15}	1.6	9.1
4×10^{15}	6.0	24
6×10^{15}	13.0	39

TABLE 1

Dose / ions cm^{-2}	TM loss / dB cm^{-1}	TE loss / dB cm^{-1}
1×10^{16}	0.1	7.0
2×10^{16}	0.5	18.0

TABLE 2



10.00
1.00
0.10
0.01
Response time / s
0.1
1.0
10.0
100.0
Irradiance / W cm-2
1. Bulk (no implantation)
2. Waveguide. Implantation = 2 x 10^15 ions cm^-2
3. Waveguide. Implantation = 4 x 10^15 ions cm^-2
4. Waveguide. Implantation = 6 x 10^15 ions cm^-2
1
2
3
4

FIGURE 1

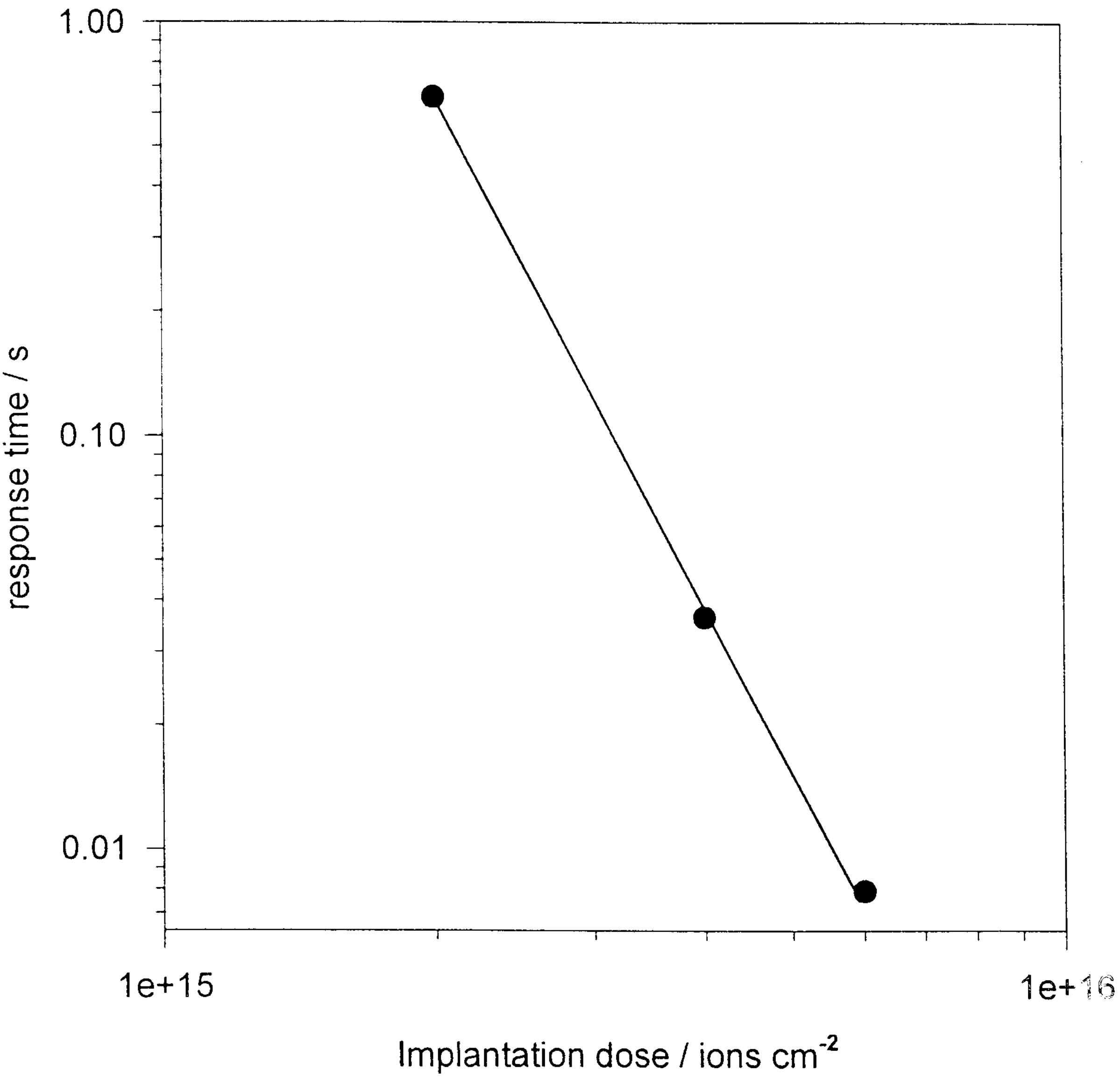
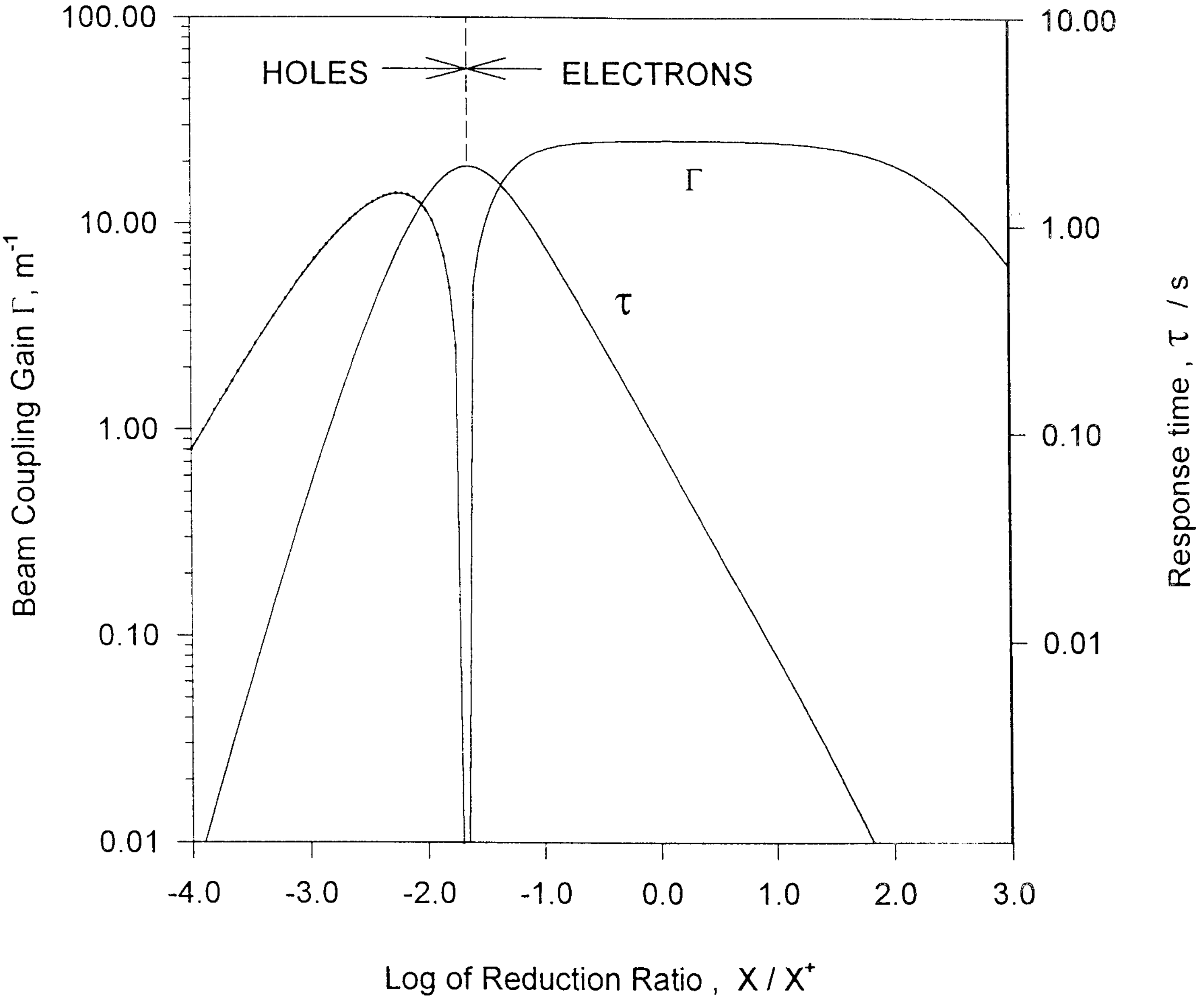

1.00
0.10
0.01
response time / s
1e+15
1e+16
Implantation dose / ions cm-2

FIGURE 2



HOLES
ELECTRONS
Γ
τ
100.00
10.00
1.00
0.10
0.01
10.00
1.00
0.10
0.01
-4.0
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0
Beam Coupling Gain Γ, m⁻¹
Response time , τ / s
Log of Reduction Ratio , X / X⁺

FIGURE 3