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Title: M-line spectroscopic, spectroscopic ellipsometric and microscopic measurements of optical waveguides fabricated by MeV-energy N+ ion irradiation for telecom applications

Article Type: EMRS 2012 Symposium W

Keywords: optical waveguide; ion beam irradiation; m-line spectroscopy; spectroscopic ellipsometry; Er-doped tungsten-tellurite glass; BGO; interference phase contrast microscopy

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Abstract: Irradiation with N+ ions of the 1.5 - 3.5 MeV energy range was applied to optical waveguide formation. Planar and channel waveguides have been fabricated in an Er-doped tungsten-tellurite glass, and in both types of bismuth germanate (BGO) crystals: $Bi_4Ge_3O_{12}$ (eulytine) and $Bi_{12}GeO_{20}$ (sillenite). Multi-wavelength m-line spectroscopy and spectroscopic ellipsometry were used for the characterisation of the ion beam irradiated waveguides. Planar waveguides fabricated in the Er-doped tungsten-tellurite glass using irradiation with N+ ions at 3.5 MeV worked even at the 1550 nm telecommunication wavelength. 3.5 MeV N+ ion irradiated planar waveguides in eulytine-type BGO worked up to 1550 nm and those in sillenite-type BGO worked up to 1330 nm.

The Guest Editor
Thin Solid Films

Subject: Submission of a trchnically improved version of an **accepted article**

Budapest, 26 August 2012

Sir,

I am herewith sending you the technically improved manuscript of our article entitled: „**M-line spectroscopic, spectroscopic ellipsometric and microscopic measurements of optical waveguides fabricated by MeV-energy N^+ ion irradiation for telecom application**" by I. Bányász *et al*., **accepted** for publication in Thin Solid Films.

I have completed all the necessary modifications to the text and figures of the article, suggested in your letter of acceptance.

I thank you for dealing with the evaluation of our manuscript.

With my best regards,

Yours sincerely

Dr. István Bányász

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Cover Letter

The Editor
Special Number of Thin Solid Films
on EMRS Symposium W
Current Trends in Optical and X-Ray Metrology of Advanced Materials for Nanoscale Devices III

Budapest, 18 July 2012
Subject: List of corrections to
M.S. No. TSF-D-12-01050

Sir,

I would like to thank you and the Reviewers for the evaluation of our manuscript, especially for the important and valuable comments and suggestions.

I am herewith sending the revised version of our article, with all the issues raised by the Reviewers addressed.

Changes made to the manuscript are indicated as underlined.

I am also uploading a file with the answers to the Reviewers' questions and comment and the complete list of modifications made to the manuscript.

With my best regards,

Yours truly

Dr. István Bányász

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The Editor
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on EMRS Symposium W
Current Trends in Optical and X-Ray Metrology of Advanced Materials for Nanoscale Devices III

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I am herewith sending the revised version of our article, with all the issues raised by the Reviewers addressed.

Changes made to the manuscript are indicated as underlined.

Answers to the Reviewers and complete list of the modifications made to the manuscript van be found in the second part of this file, beginning with Reviewer No. 1. The Reviewers' questions and comments are reproduced in *italics*.

With my best regards,

Yours truly

Dr. István Bányász

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LIST OF CORRECTION MADE IN THEREVISED VERSION OF M.S. No. TSF-D-12-01050
M-line spectroscopic, spectroscopic ellipsometric and microscopic measurements of optical waveguides fabricated by MeV-energy N^+ ion irradiation for telecom applications
by Bányász et al.

1. Issues raised by Reviewer #1:

1) In the Abstract, the authors claimed that a method was developed. I don't think it reflect the correct description of the research topics. The implantation of ions has been developed as a unique technique to fabricate waveguides in optical materials. N is one selected ion. It is not reasonable to claim this work reported a method. In addition, the authors should also demonstrate the reason why they used N ions instead of others.

We have made the following modifications to comply with the above request:

We exchanged first sentence of the **Abstract**

A method for fabrication of optical waveguides in amorphous and crystalline materials via irradiation with N^+ ions of the 1.5 – 3.5 MeV energy range has been developed.

with

Irradiation with N^+ ions of the 1.5 – 3.5 MeV energy range was applied to optical waveguide formation.

We added the following paragraph just after the first paragraph of Chapter 2 (**Waveguide fabrication)**

We decided to use MeV – energy N^+ ions for the fabrication of waveguides because of some excellent results published by other research groups on N^+ ion irradiated optical waveguides and our own favourable experiences with that ion. Hubler *et al.* fabricated high refractive index contrast planar waveguides in silicon using high-energy (0.67 – 3.17 MeV) and high-fluence (0.25×10^{18} – 1.65×10^{18} ions/cm^2) N^+ irradiation [11]. More recently, Ren *et al*. reported successful fabrication of waveguide lasers in Nd: YAG crystal via irradiation with 20 MeV N^+ ions at a fluence of 2×10^{14} ions/cm^2 [12]. In an earlier experiment of Bányász *et al*., optical transmission gratings were fabricated in Pyrex glass using MeV-energy He^+ and N^+ ions [13]. It was found that N^+ irradiation of the same energy and fluence produced an order of magnitude higher optical path modulation in the irradiated sample than He^+ irradiation.

We added the following references:

[11] G.K. Hubler, P.R. Malmberg, and T.P. Smith III, J. Appl. Physics 50 (1979) 7147
[12] Y. Ren, N. Dong, F. Chen, and D. Jaque, Optics Express 19 (2011) 5522
[13] I. Bányász, M. Fried, Cs. Dücső and Z.Vértesy, Applied Physics Letters 79 (2001) 3755

2) The authors used N ion implantation with fluencies of 2-16e15 ions/cm2. I think lower fluence at ~2e14 ions/cm2 maybe also work for BGO crystals. So the authors should explain why they use high fluence implantations. In fact, for so-called heavy (or medium-mass) ions, the typical ion fluence is at order of 10^14 ions/cm2.

We have made the following modifications to comply with the above request:

We added a new paragraph to Chapter 2 (**Waveguide fabrication),** immediately **after Table 1**.:

According to our previous investigations [7], MeV energy N^+ irradiations at high fluences resulted in the formation of a barrier layer around the stopping range of the ions. The fluences indicated in **Table 1** were appropriate to obtain sufficiently large refractive index difference between the well and the barrier for guiding.

3) The waveguide losses can be measured by using back-reflection method even for short samples. Any method for ion implanted waveguide has its own advantages and shortcomings. The authors should not expect too much from longer samples. For high-loss waveguides, the surface scattering method reflects sometimes very wrong results.

We have made the following modifications to comply with the above request:

We added the following sentence to Chapter **6. Conclusion,** on page 18 line 5:

Besides of the double prism method, propagation losses will be measured by the back-reflection method, too.

4) Only showing the modal lines is a not a direct proof for a real waveguide. For some ion implanted waveguides, one can detect beautiful modes, but the light cannot go through the waveguides with a simple end-face coupling system. So what I suggest for the future work is not to make more samples but to first test the propagation (transmission) of light in the waveguide. This can be stated in the Conclusion section.

We have made the following modifications to comply with the above request:

We added the following sentence before the last sentence of the **6. Conclusion** Chapter:

It is planned that guiding will be checked in all the suitable N^+ - irradiated samples by end-face coupling

LIST OF CORRECTION MADE IN THEREVISED VERSION OF M.S. No. TSF-D-12-01050
M-line spectroscopic, spectroscopic ellipsometric and microscopic measurements of optical waveguides fabricated by MeV-energy N^+ ion irradiation for telecom applications
by Bányász et al.

2. Issues raised by Reviewer #2:

Firstly the paper is not particularly well written. The introduction does not critically review past studies and as a result it is not clear how this present study is novel or different.

Since this article is not a review, detailed discussion of previous art is outside its scope. This article is based on an oral presentation given at Symposium W- Current Trends in Optical and X-Ray Metrology of Advanced Materials for Nanoscale Devices III of the 2012 Spring meeting of the EMRS Society, our aim was to present the following novelties of our results:

1. Application of spectroscopic ellipsometry to the quantitative study of (ion beam irradiated) planar optical waveguides
2. Comparison of the spectroscopic ellipsometric results with the predictions of SRIM simulations
3. Multi-wavelength m-line spectroscopic study of ion beam irradiated planar optical waveguides, up to the 1.5 μm telecom wavelength

We have compared our methods and results in the field of ion beam irradiated optical waveguides to those obtained by other research groups in other publications. Our relevant publications are cited in this article.

Furthermore there is no explanation as to why the samples analyzed in this study were chosen. Why not just focus on one sample and properly analyze a full set of results and measurements, and study loss and annealing behavior? Why were channel waveguides made only for one sample type?

Choice of samples is explained in chapter **1. Introductio**n, with 3 references on Er: Te glass and 4 references on the two types of BGO.

This article does not focus at channel waveguides. **Fig.1** was included only to show a possibility for optical (microscopic) localization of the irradiated waveguides.

We have made the following modifications to comply with the above request:

We have removed all the results obtained in CaF_2 crystals. Those results will be published in another article.

The subsequent sections state the experiments performed, again no explanation is offered as to why certain energies, ion species and fluences were chosen. The results section just tabulates the measurements again without any proper discussion about the observed results.

We have made the following modifications to comply with the above request:

We have added the following reference:

[14] I. Bányász, S. Berneschi, M. Bettinelli, M. Brenci, M. Fried, N.Q. Khanh, T. Lohner, G. Nunzi Conti, S. Pelli, P. Petrik, G.C. Righini, A. Speghini, A. Watterich, Z. Zolnai, IEEE Photonics Journal, 4 (2012) 721

We added the following new paragraph to Chapter **2. Waveguide fabrication,** after the third paragraph, from line 18 on:

Ion energies were limited by the terminal voltage of the accelerator, 5 MV, and the available ions. Only single-charged ions could be used. This resulted in 3.5 MeV as the upper limit of N^+ energy. Results of our more recent experiments proved that planar waveguides fabricated with 3.5 MeV N^+ irradiation supported modes up to 1.5 μm, both in BGO crystals [9] and Er: Te glass [14]. Irradiated fluence ranges were chosen based on results of our previous experiments, so as to achieve the necessary refractive index modulation in the waveguides.

Some data (Calcium fluoride) is incomplete or the authors were unable to make accurate measurements so why even include this data? Is it enough to show that waveguides "worked". The refractive index data is useful and maybe as part of a more focused paper would be interesting.

The reviewer was right when he or she claimed that we should have presented results obtained with **less materials**.

We have made the following modifications to comply with the above request:

We have removed all the results obtained in CaF_2 crystals. Those results will be published in another article.

Abstract:

"A method for fabrication of optical waveguides in amorphous and crystalline materials via irradiation with N+ ions of the 1.5 - 3.5 MeV energy range has been developed."

Ion implantation is a well established "method" of producing waveguides. There is no new development presented here.

We have made the following modifications to comply with the above request:

We exchanged first sentence of the **Abstract**

A method for fabrication of optical waveguides in amorphous and crystalline materials via irradiation with N^+ ions of the 1.5 – 3.5 MeV energy range has been developed.

with

Irradiation with N^+ ions of the 1.5 – 3.5 MeV energy range was applied to optical waveguide formation.

Introduction:
"It has better controllability and reproducibility than other techniques."
What other techniques? There is no comparison made in the text. Are you comparing with laser writing? ion exchange ? What criteria are you using to judge which technique is better ? No references are given.

How did you choose the materials to investigate ? The introduction should contain a clear description of the motivation behind the study. None is given. Only a brief review of similar studies is given and no description on how the current study builds on these previous results. It is therefore difficult to judge whether this current study is novel.

Answer to the above questions can be found among the answers given to the very first question of Reviewer No. 2.

We have made the following modifications to comply with the above request:

We removed the following sentence from line 3 of the **Introduction**:

It has better controllability and reproducibility than other techniques

Why are so many different materials chosen ?

As mentioned earlier, to comply with this objection of the Reviewer, we have removed all the results concerning CaF_2.

"Successful waveguide fabrication in alkali fluoride and alkali earth halide crystals using only light ions (H+ and He+) has been reported so far"

What is the difference between light ions and N for making waveguides ? Why is it interesting to use heavy ions ?

This question of Reviewer No. 2 was posed by Reviewer No. 1 in his or her Question No.1.

We have made the following modifications to comply with the above request:

We added the following paragraph just after the first paragraph of Chapter 2 (**Waveguide fabrication)**

We decided to use MeV – energy N^+ ions for the fabrication of waveguides because of some excellent results published by other research groups on N^+ ion irradiated optical waveguides and our own favourable experiences with that ion. Hubler *et al.* fabricated high refractive index contrast planar waveguides in silicon using high-energy (0.67 – 3.17 MeV) and high-fluence (0.25×10^{18} – 1.65×10^{18} ions/cm^2) N^+ irradiation [11]. More recently, Ren *et al*. reported successful fabrication of waveguide lasers in Nd: YAG crystal via irradiation with 20 MeV N^+ ions at a fluence of 2×10^{14} ions/cm^2 [12]. In an earlier experiment of Bányász *et al*., optical transmission gratings were fabricated in Pyrex glass using MeV-energy He^+ and N^+ ions [13]. It was found that N^+ irradiation of the same energy and fluence produced an order of magnitude higher optical path modulation in the irradiated sample than He^+ irradiation.

We added the following references:

[11] G.K. Hubler, P.R. Malmberg, and T.P. Smith III, J. Appl. Physics 50 (1979) 7147
[12] Y. Ren, N. Dong, F. Chen, and D. Jaque, Optics Express 19 (2011) 5522
[13] I. Bányász, M. Fried, Cs. Dücső and Z.Vértesy, Applied Physics Letters 79 (2001) 3755

Waveguide fabrication:
Not enough details given. The text just states the combination of beam energy and samples irradiated. It is also contained in the tables. No explanation as to why these combinations were chosen.

We have made the following modifications to comply with the above request:

1. See the answers and actions given to the previous questions of Reviewer No. 2.

Why are single energy implantation chosen for some samples and multi energy for others ?

We have made the following modifications to comply with the above request:

We added the following sentence to line 5 of paragraph 3 of Chapter **2. Waveguide fabrication**:

Irradiation at two different ion energies was chosen to suppress leaky modes by forming a broader barrier layer.

"Distribution of the implanted ions or that of the collision events along the depth of the implanted sample can serve as rough estimation of the refractive profile of the implanted waveguide."

This is a little simplistic. What about other effects, stress, polarizability ? What about the differences between crystals and amorphous materials like glass ? Refractive index can increase or decrease upon implantation.

We completely agree with the Reviewer. However, we would like to stress again that it is not the goal of this article to discuss in detail the possible physical mechanisms of waveguide formation. We did it in our publications cited in this article.

"An INTERPHAKO microscopic image of a corner of a planar waveguide implanted in a CaF2 sample with 3.5 MeV N+ at a fluence of 2 ?1016 is presented in Fig. 2. It was taken with a Zeiss Peraval microscope in transmission. Note the relatively low contrast."
In this image really necessary? It doesn't need to be a separate figure.

We have made the following modifications to comply with the above request:

We have removed all the results obtained in CaF_2 crystals. Those results will be published in another article.

"Dielectric functions of the first and second layers were described by the Cauchy dispersion relation."

Is the Cauchy relation really appropriate here ? This is usually used for polymers, not crystals or glass. Any discussion or reference to show otherwise?

We have made the following modifications to comply with the above request:

Cauchy dispersion relation describes correctly the dielectric functions when photon energy is lower than the band gap of the dielectrics. To avoid fitting problems at the UV wavelengths, we used only the $\lambda > 400$ nm part of the measured ellipsometric spectra for the simulations.

Table 2 shows refractive index data fro 635nm. If 1550nm is so important (See introduction) then why don't you show data for 1550nm ?

The Reviewer is right, calculated refractive indices at λ = 1550 nm are also important.

We have made the following modifications to comply with the above request:

We inserted two rows in both **Table 2.** and Table **3.** with the refractive indices of $layer_2$ and $layer_1$ at 1550 nm, obtained from the SE simulations.

You have not described what you mean by "barrier boundaries " that are shown in figures 3,4 and 5. You need to improve the discussion here.

We have made the following modifications to comply with the above request:

We added the following text to Chapter *4.1 Results for Er: Te glass*, after line 4:

The blue and red line pairs in Fig. 2 represent the two boundaries of the barrier layer (layer1) of the irradiated waveguides, obtained from the spectroscopic ellipsometric simulations. The well (layer2) is delimited by the sample surface (z = 0 μm) and the upper (left) boundary of the barrier.

"This may be attributed to the fact that SRIM slightly overestimates stopping power, and consequently predicts lower ranges than the experimental ones. [19, 20]"

Did you check that you were not channeled by doing RBS during the irradiation?

Such RBS check was not possible.

We write the following in Chapter **2. Waveguide fabrication:**

"Irradiations were carried out with 1.5 MeV - 3.5 MeV N^+ collimated beam from a Van de Graaff accelerator (available at the Wigner Research Centre for Physics, Budapest), with normal incidence on the glass samples and at 7° incidence on the BGO crystal samples, to avoid channeling."

In our opinion, and according to common practice, that is a reasonable measure to avoid channeling. Moreover, even in case channeling occurs (in other configurations) when irradiating at high fluences (10^{16} ions/xm^2 or above), only a small fraction (about the first 10 %) of the total fluence would pass beyond the calculated stopping range before radiation damage would close the channel.

"Discrepancies between SRIM and SE results are much higher in the case of the two BGO crystals than in the case of Er: Te glass. The large deviations are due to serious convergence problems in SE simulations rather than stopping powers overestimated by SRIM."

No explanation or reference given to justify this statement.

We have made the following modifications to comply with the above request:

In the last paragraph of Chapter 4.2 Results for BGO crystals, on page 11 we replaced the following text

Discrepancies between SRIM and SE results are much higher in the case of the two BGO crystals than in the case of Er: Te glass. The large deviations are due to serious convergence problems in SE simulations rather than stopping powers overestimated by SRIM.

with:

The relatively large differences between the positions of the boundaries obtained by spectroscopic ellipsometric simulations, and that of the peak of the N^+ distribution cannot be attributed exclusively to the fact that SRIM overestimates stopping power [18, 19]. It may be due to the convergence problems we experienced in the spectroscopic ellipsometric simulations.

4.2 Results for CaF2 crystal

"Only one result can be presented. Implanted N+ distribution in the CaF2 crystal, obtained by SRIM, and barrier layer boundaries of a waveguide obtained by SE are shown in Figure 5."

This section is very short! One figure. Why even include this data in the paper ?

We have made the following modifications to comply with the above request:

We have removed all the results obtained in CaF_2 crystals. Those results will be published in another article.

5. M-line spectroscopy

"All the measurements presented here were performed in TE configuration."
Why only TE, can you justify why TM not measured. It can be important for crystals.

It is quite simple to calculate the number of modes one might expect for a particular design, especially for planar waveguides. Can you compare these with you m-line measurements ?

We have made the following modifications to comply with the above request:

We added the following text to Chapter *5.1 Results for Er: Te glass*, on page 12, line 12, just before **Fig. 4**:

Number and positions of dark lines correspond to our calculations published recently [14].

Conclusion:

"Waveguides written in Bi4Ge3O12 remained operative up to <lambda> = 1550 nm" What do you mean by waveguide remain operative? Y=No loss data is shown so I cannot judge whether the technique produces useful waveguide in these materials.

"Experiments with thermal annealing of the irradiated waveguides to improve their quality will be carried out in the near future."
Include these in a revised paper. Measure loss before and after and say something about the loss mechanism.

Unfortunately, our m-line spectrometer had been down for a long time, so that no additional measurements could be performed.

We have made the following modifications to comply with the above request:

In the Chapter **Conclusion,** on page 17 line 11 we replaced the text

Beginning from an implanted fluence of 5 x 10^{14} ions/cm^2, all waveguides fabricated in the tellurite glass did work.

with

Beginning from an implanted fluence of 5 x 10^{14} ions/cm^2, modes could be detected with m-line spectroscopy in all tellurite glass waveguides.

In the Chapter **Conclusion,** on page 17 line 13 we replaced the text

Waveguides implanted with N^+ ions of 3.5 MeV energy and at double-energy at 3.5 + 3.0 MeV and 3.5 + 2.5 MeV worked at 1550 nm, too.

with

Modes were detected at 1550 nm, too in waveguides implanted with N^+ ions of 3.5 MeV energy and at double-energy at 3.5 + 3.0 MeV and 3.5 + 2.5 MeV.

In the Chapter **Conclusion,** on page 17 line 18 we replaced the text

Waveguides written in $Bi_4Ge_3O_{12}$ remained operative up to $\lambda = 1550$ nm, while those in $Bi_{12}GeO_{20}$ worked up to 1310 nm.

with

Modes could be observed up to 1550 nm in waveguides written in $Bi_4Ge_3O_{12}$, and up to 1310 nm in those written in $Bi_{12}GeO_{20}$.

We added the following sentence to Chapter **6. Conclusion,** on page 18 line 5:

Besides of the double prism method, propagation losses will be measured by the back-reflection method, too.

***Highlights (for review)**

- Waveguides were fabricated in glass and crystals using MeV energy N^+ ions.
- SRIM simulation and spectroscopic ellipsometry yielded similar waveguide structures.
- Multi-wavelength m-line spectroscopy was used to study the waveguides.
- Waveguides fabricated in an Er-doped tungsten-tellurite glass worked up to 1.5 μm.
- Waveguides in $Bi_{12}GeO_{20}$ remained operative up to 1.5 μm.

M-line spectroscopic, spectroscopic ellipsometric and microscopic measurements of optical waveguides fabricated by MeV-energy N^+ ion irradiation for telecom applications

I. Bányász[a*], S. Berneschi[b, c], M. Fried[d], T. Lohner[d], G. Nunzi Conti[c], G.C. Righini[c], S. Pelli[c], Z. Zolnai[d]

[a] Wigner Research Centre for Physics, Hungarian Academy of Sciences, P.O.B. 49, H-1525, Budapest, Hungary

[b] "Enrico Fermi" Center for Study and Research, Piazza del Viminale 2, 00184 Roma, Italy

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[d] Institute of Technical Physics and Materials Science, Research Centre for Natural Sciences, Hungarian Academy of Sciences, P.O.B. 49, H-1525, Budapest, Hungary

Abstract

Irradiation with N^+ ions of the 1.5 – 3.5 MeV energy range was applied to optical waveguide formation. Planar and channel waveguides have been fabricated in an Er-doped tungsten-tellurite glass, and in both types of bismuth germanate (BGO) crystals: $Bi_4Ge_3O_{12}$ (eulytine) and $Bi_{12}GeO_{20}$ (sillenite).

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E-mail address: banyasz@sunserv.kfki.hu (I. Bányász)

Multi-wavelength m-line spectroscopy and spectroscopic ellipsometry were used for the characterisation of the ion beam irradiated waveguides. Planar waveguides fabricated in the Er-doped tungsten-tellurite glass using irradiation with N^+ ions at 3.5 MeV worked even at the 1550 nm telecommunication wavelength. 3.5 MeV N^+ ion irradiated planar waveguides in eulytine-type BGO worked up to 1550 nm and those in sillenite-type BGO worked up to 1330 nm.

1. Introduction

Ion implantation, compared with other waveguide fabrication methods, has some unique advantages. It proved to be a universal technique for producing waveguides in most optical materials [1]. The first articles reporting fabrication of waveguides by ion implantation appeared between the end of 1960's and early 1980's. The first ion implanted waveguides were produced in 1968 by proton implantation into fused silica glass [2]. A detailed review on ion-implanted optical waveguides has been published recently [3].

Tellurite glasses have gained a widespread attention because of their potential as hosts of rare-earth elements for the development of fibre and integrated optic amplifiers and lasers covering all the main telecommunication bands [4, 5]. Er^{3+} doped tellurite glasses in particular are very attractive materials for the fabrication of broadband amplifiers in wavelength division multiplexing (WDM) around 1.55 μm, as they exhibit large stimulated cross sections and broad emission bandwidth [6]. Fabrication of channel waveguides in an Er-doped tungsten-tellurite glass has recently been reported [7].

Bismuth germanate (BGO) is a well known scintillator material. Due to its high electro-optic coefficients, it is used in nonlinear optics, e.g. for building Pockels cells, and can also be used

in the fabrication of photorefractive devices. Formation of planar waveguides in $Bi_4Ge_3O_{12}$ (eulytine) crystals by implantation of He^+ ions of the 1 - 2 MeV energy range was reported by Mahdavi et al. [8]. Preliminary results in fabricating planar waveguides in both eulytine and sillenite type bismuth germanate crystals using MeV energy N^+ ions were reported by Bányász *et al.* [9]. Yang *et al.* formed planar waveguides in $Bi_4Ge_3O_{12}$ crystals via irradiation with 17 MeV C^{5+} and O^{5+} ions at relatively low fluences [10].

2. Waveguide fabrication

Composition of the Er: Te glass we developed for our experiments was 60 TeO_2-25 WO_3-15 Na_2O-0.5 Er_2O_3 (mol. %).

We decided to use MeV – energy N^+ ions for the fabrication of waveguides because of some excellent results published by other research groups on N^+ ion irradiated optical waveguides and our own favourable experiences with that ion. Hubler *et al.* fabricated high refractive index contrast planar waveguides in silicon using high-energy (0.67 – 3.17 MeV) and high-fluence (0.25×10^{18} – 1.65×10^{18} ions/cm^2) N^+ irradiation [11]. More recently, Ren *et al*. reported successful fabrication of waveguide lasers in Nd: YAG crystal via irradiation with 20 MeV N^+ ions at a fluence of 2×10^{14} ions/cm^2 [12]. In an earlier experiment of Bányász *et al*., optical transmission gratings were fabricated in Pyrex glass using MeV-energy He^+ and N^+ ions [13]. It was found that N^+ irradiation of the same energy and fluence produced an order of magnitude higher optical path modulation in the irradiated sample than He^+ irradiation.

Five types of planar waveguides were fabricated using the following ion - target combinations: 1.5 MeV N^+ ions implanted into Er: Te glass, using a wide range of implanted fluences, 3.5 MeV N^+ ions implanted into Er: Te glass, Double-energy N^+ ions implanted into Er: Te glass, 3.5 MeV N^+ ions implanted into $Bi_4Ge_3O_{12}$ (eulytine) single crystals and 3.5

MeV N^+ ions implanted into $Bi_{12}GeO_{20}$ (sillenite) single crystals. Irradiation at two different ion energies was chosen to suppress leaky modes by forming a broader barrier layer.

Ion energies were limited by the terminal voltage of the accelerator, 5 MV, and the available ions. Only single-charged ions could be used. This resulted in 3.5 MeV as the upper limit of N^+ energy. Results of our more recent experiments proved that planar waveguides fabricated with 3.5 MeV N^+ irradiation supported modes up to 1.5 μm, both in BGO crystals [9] and Er: Te glass [14]. Irradiated fluence ranges were chosen based on results of our previous experiments, so as to achieve the necessary refractive index modulation in the waveguides.

Irradiations were carried out with 1.5 MeV - 3.5 MeV N^+ collimated beam from a Van de Graaff accelerator (available at the Wigner Research Centre for Physics, Budapest), with normal incidence on the glass samples and at 7° incidence on the BGO crystal samples, to avoid channeling. Lateral homogeneity of the irradiation was ensured by defocusing the ion beam with a magnetic quadrupole and by scanning the sample under a 2 mm x 2 mm beam. Useful size of the implanted waveguides was 6 mm x 6 mm.

Names and implanted fluences of the planar waveguides implanted in Er: tellurite glass by 1.5 MeV , 3.5 MeV and double-energy N^+ ions, in $Bi_4Ge_3O_{12}$ and $Bi_{12}GeO_{20}$ crystals, all by 3.5 MeV N^+ ions, are shown in **Table 1**.

Table 1. Summary of the implantation energies and fluences for all the waveguides

		Names of the waveguides and implanted fluences ($x10^{15}$ ions/cm^2)							
Name of the target	N+ energy (MeV)	A	B	C	D	E	F	G	H
Er: Te glass	1,5	0.005	0.05	0.5	5	10	20	40	80
Er: Te glass	3.5	10	20	40	80	-	-	-	-
Er: Te glass, 2 energy	3.5, 3.5+3.0, 3.5+2.5	40	40	40					
$Bi_4Ge_3O_{12}$	3.5	2	4	8	16	-	-	-	-
$Bi_{12}GeO_{20}$	3.5	2	4	8	16	-	-	-	-

According to our previous investigations [7], MeV energy N^+ irradiations at high fluences resulted in the formation of a barrier layer around the stopping range of the ions. The fluences indicated in **Table 1** were appropriate to obtain sufficiently large refractive index difference between the well and the barrier for guiding.

Structure of the ion implanted planar waveguides is determined mainly by the energy and fluence of the implanted ions. Distribution of the implanted ions or that of the collision events along the depth of the implanted sample can serve as rough estimation of the refractive index profile of the implanted waveguide. We used SRIM 2012 [15] code (Stopping and Range of Ions in Matter) to simulate the fabrication of the ion-implanted planar waveguides. We performed SRIM calculations for each experiment, using the full damage cascades option with 5000 ions.

Maxima of the distributions of the implanted N^+ ions are at 1.6 μm and 2.6 μm below the surface of the Er: Te glass sample in case of 1.5 MeV and 3.5 MeV ion energies with longitudinal stragglings of 0.35 μm and 0.50 μm. Maxima of the collision events (vacancy production) distributions roughly coincide with those of the ion distributions, but they extend considerably towards sample surface. When double-energy irradiation at energies of 3.5 MeV and 2.5 MeV was applied, and N^+ ion distribution was approximated by the algebraic sum of those obtained at the single energies, centre of the resulting distribution shifted to 2.4 μm and its width increased to 0.90 μm.

Range and longitudinal straggling of 3.5 MeV N^+ ions in $Bi_4Ge_3O_{12}$ were found to be 2.29 μm and 0.28 μm. The same parameters are 2.02 μm and 0.28 μm for $Bi_{12}GeO_{20}$.
All the samples were cleaned by plasma stripping after irradiation to remove any possible contamination from the vacuum system.

3. Optical microscopy

Optical microscopy was used mainly to localise waveguides on the substrate. Interference phase contrast microscopy (INTERPHAKO) was used to detect refractive index changes in the waveguides [16]. A composite INTERPHAKO microphotograph of channel waveguides implanted in an Er: Te glass sample is shown in **Fig. 1**. The microphotographs were taken with a Nikon Labophot microscope in reflection. Optical path differences are converted into differences in the hue of the interference colours. Note that INTERPHAKO mocrophotographs prove at the first sight that refractive index modulation increases with N^+ fluence.

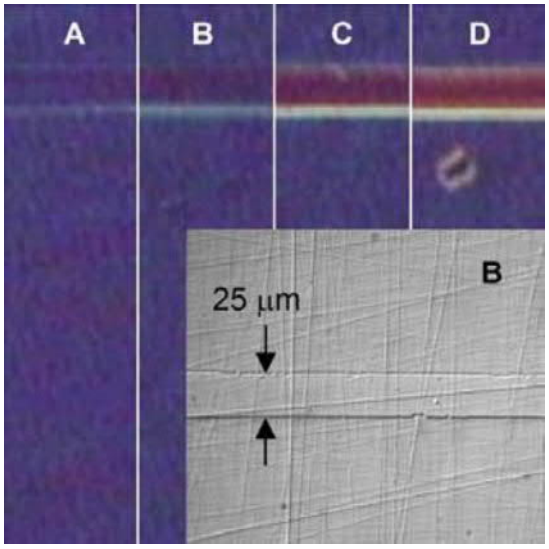


Fig. 1. Interference phase contrast microscopic image of channel waveguides implanted in an Er: Te glass sample. The fluences were 0.5, 1, 2, and $4x10^{16}$ ions/cm^2 in stripes A, B, C, and D. Conventional optical microscopic image of stripe B is also shown in the inset.

4. Spectroscopic ellipsometry

All the ion-implanted waveguides were measured with a WOOLLAM M-2000DI spectroscopic ellipsometer (λ = 193-1690 nm), except of the 1.5 MeV N^+ irradiated Er:Te glass samples, where .a SOPRA ES4G ellipsometer was used in the λ = 400 -1000 nm range. A three-layer optical model was applied in the evaluation of the spectroscopic

ellipsometry (SE) data. The first layer, adjacent to the substrate, represents the stopping region. The second layer is the region that the implanted ions traverse before they stop. The third layer is a surface roughness film taken into account on basis of effective medium approximation [17]. Dielectric functions of the first and second layers were described by the Cauchy dispersion relation. Parameters of the Cauchy dispersion relations and layer thicknesses were considered as free parameters. Cauchy dispersion relation describes correctly the dielectric functions when photon energy is lower than the band gap of the dielectrics. To avoid fitting problems at the UV wavelengths, we used only the $\lambda > 400$ nm part of the measured ellipsometric spectra for the simulations. We applied the evaluation software WVASE32 created by J.A. Woollam©, Inc [18] for the analysis of the spectroellipsometric data.

4.1 Results for Er: Te glass

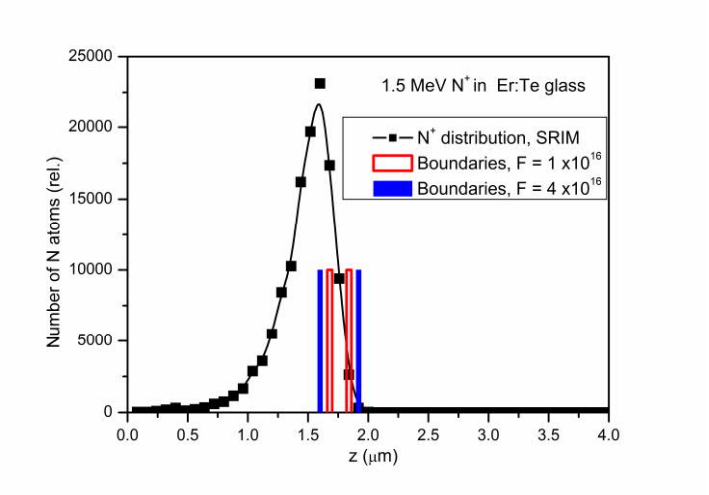
Results of the SE simulations for the waveguides in Er: Te glass are summarised in **Table 2.**

Table 2. Results of spectroscopic ellipsometric measurements of Er: tellurite glass waveguides

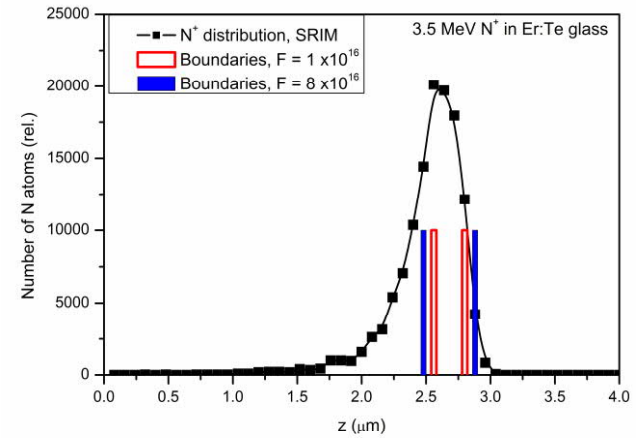
N+ energy (MeV)	1.5				3.5			
Names of the waveguides	E	F	G	H	A	B	C	D
Fluences ($x10^{16}$ ions/cm^2)	1	2	4	8	1	2	4	8
Thickness of $layer_2$ [nm]	1781 ± 19	1785 ± 28	1779 ± 16	-	2615.1 ± 1.6	2643.6 ± 14.5	2403.8 ± 5.1	2384.7 ± 4.6
Refractive index of $layer_2$ at 635 nm	2.052	2.048	2.052	-	2.063	2.042	2.040	2.097
Refractive index of $layer_2$ at 1550 nm					1.984	1.965	1.969	1.962
Thickness of $layer_1$ [nm]	67 ± 22	83 ± 35	97 ± 19	-	183.4 ± 9.8	195.8 ± 4.6	457.3 ± 4.7	489.8 ± 8.6
Refractive index of $layer_1$ at 635 nm	2.071	2.068	2.071	-	2.014	2.025	2.070	2.004
Refractive index of $layer_1$ at 1550 nm					1.954	1.955	1.936	1.960
Refractive index of the non-implanted glass at 635 nm	2.081	2.081	2.081	-	2.019	2.019	2.019	2.019
Refractive index of the non-implanted glass at 1550 nm					1.950	1.950	1.950	1.950

Due to the rather low refractive index changes and the simple model, the above data can give only a rough approximation of the waveguide structure.

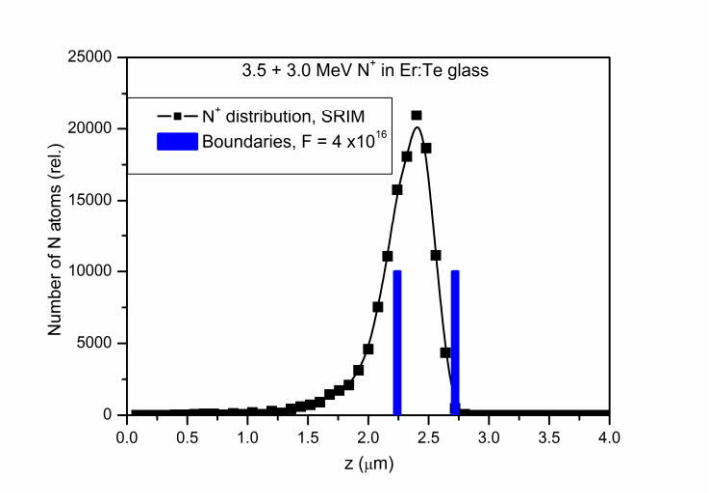
Graphical comparison of implanted N^+ distributions in the Er: Te glass, obtained by SRIM, and barrier layer boundaries obtained by SE is shown in **Figure 2**.



a)



b)



c)

Fig. 2. SRIM simulation and SE fit of the waveguide structure in Er: Te glass at various irradiation energies and fluences: **a)** E = 1.5 MeV, fluences are $1 \cdot 10^{16}$ and $4 \cdot 10^{16}$. **b)** E = 3.5 MeV, fluences are $1 \cdot 10^{16}$ and $8 \cdot 10^{16}$ ions/cm^2. **c)** E = 3.5 MeV + 3.0 MeV, fluence is $4 \cdot 10^{16}$ ions/cm^2.

The blue and red line pairs in **Fig. 2** represent the two boundaries of the barrier layer (layer$_1$) of the irradiated waveguides, obtained from the spectroscopic ellipsometric simulations. The well (layer$_2$) is delimited by the sample surface (z = 0 μm) and the upper (left) boundary of the barrier.

Barrier boundaries calculated with the simple model from the spectroscopic ellipsometric data are close to the maximum of the N^+ distribution, calculated with SRIM. Larger longitudinal straggling and higher fluence result in thicker barrier layers, as expected. Centre of the calculated barrier layer is shifted downwards with respect to the centre of the N^+ distribution. This may be attributed to the fact that SRIM slightly overestimates stopping power, and consequently predicts lower ranges than the experimental ones [19, 20].

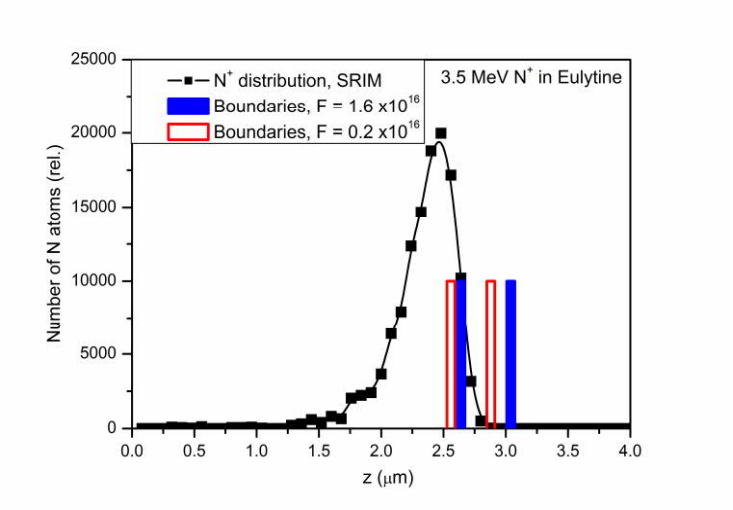
4.2 Results for BGO crystals

Results of the SE simulations for BGO waveguides are presented in **Table 3.**

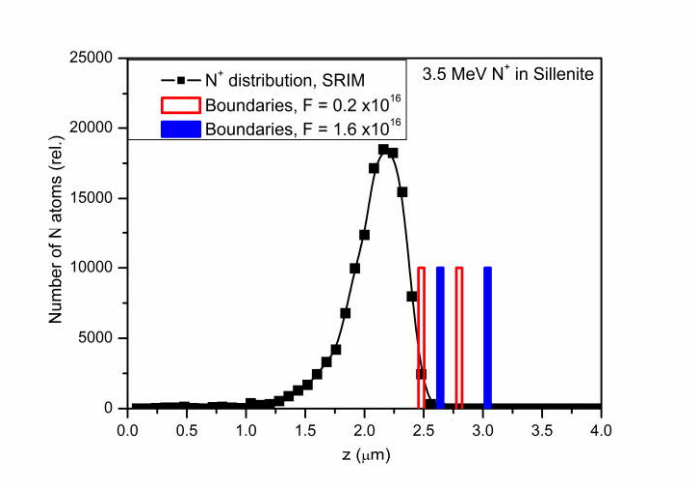
Table 3. Results of spectroscopic ellipsometric measurements of BGO waveguides

BGP crystal type	$Bi_4Ge_3O_{12}$				$Bi_{12}GeO_{20}$			
Names of the waveguides	A	B	C	D	A	B	C	D
Fluences ($x10^{16}$ ions/cm^2)	0.2	0.4	0.8	1.6	0.2	0.4	0.8	1.6
Thickness of $layer_2$ [nm]	2552.7 ± 0.9	2575.8 ± 1.1	2632.9 ± 0.9	2628.1 ± 0.8	2500.2 ± 21.6	2571.6 ± 3.1	2588.2 ± 3.1	2685.7 ± 1.70
Refractive index of $layer_2$ at 635 nm	2.115	2.130	2.109	2.125	2.393	2.380	2.382	2.368
Refractive index of $layer_2$ at 1550 nm	2.065	2.068	2.058	2.063	2.333	2.3	2.358	2.330
Thickness of $layer_1$ [nm]	337.9 ± 10.6	287.9 ± 2.9	346.4 ± 4.2	412.9 ± 4.6	294.9 ± 42.5	517.9 ± 19.5	472.8 ± 27.4	348.2 ± 9.2
Refractive index of $layer_1$ at 635 nm	2.087	2.086	2.085	2.088	2.370	2.549	2.467	2.650
Refractive index of $layer_1$ at 1550 nm	2.041	2.037	2.038	2.035	2.418	2.308	2.395	2.26
Refractive index of the non-implan`ted glass at 635 nm	2.085	2.085	2.085	2.085	2.487	2.487	2.487	2.487
Refractive index of the non-implanted glass at 1550 nm	2.049	2.049	2.049	2.049	2.410	2.410	2.410	2.410

Implanted N^+ distributions in the two types of BGO crystals, obtained by SRIM, and barrier layer boundaries obtained by SE are shown in **Figure 3**.



a)



b)

Fig. 3 a) SRIM simulation and SE fit of the waveguide structure in BGO with 3.5 N^+ irradiation at various fluences: **a)** Eulytine, fluences are $0.2 \cdot 10^{16}$ and $1.6 \cdot 10^{16}$. **b)** Sillenite, fluences are $0.2 \cdot 10^{16}$ and $1.6 \cdot 10^{16}$ ions/cm^2.

The relatively large differences between the positions of the boundaries obtained by spectroscopic ellipsometric simulations, and that of the peak of the N^+ distribution cannot be attributed exclusively to the fact that SRIM overestimates stopping power [19, 20]. It may be due to the convergence problems we experienced in the spectroscopic ellipsometric simulations.

5. M-line spectroscopy

COMPASSO, a semi-automatic m-line spectroscopic instrument, developed at IFAC, was used for the characterization of the planar waveguides implanted in the samples. Accuracy of the instrument is generally $\pm 1 \cdot 10^{-4}$ and $\pm 4 \cdot 10^{-4}$ on the effective refractive index and bulk refractive index, respectively. In the case of the N^+-implanted planar waveguides in the Er: Te glass, due to the lower contrast in the measurement, the accuracy was lower, about $\pm 5 \cdot 10^{-4}$ and $\pm 1 \cdot 10^{-3}$ respectively. Due to the high refractive index of the bulk Er: Te glass (around 2.0

at 635 nm), and even higher of the sillenite BGO (about 2.55 at 635 nm) we used special rutile prisms to couple the light in the irradiated regions. All the measurements presented here were performed in TE configuration.

5.1 Results for Er: Te glass

The waveguide irradiated with 1.5 MeV N^+ ions supported guiding modes up to 980 nm in the fluence range between $1 \cdot 10^{16}$ and $8 \cdot 10^{16}$ ions/cm^2. They were not operative at 1310 and 1550 nm.

Increasing irradiation energy to 3.5 MeV resulted in thicker well layers that could facilitate operation at longer wavelengths. Indeed, m-line spectroscopic measurements showed that one fundamental guiding mode could be observed at 1550 nm in the waveguides irradiated in an Er: Te glass sample with fluences between $1 \cdot 10^{16}$ and $1 \cdot 10^{16}$ ions/cm^2. M - line spectra of a waveguide irradiated with 3.5 MeV N^+ at a fluence of $8 \cdot 10^{16}$ ions/cm^2 measured at 635 and 1550 nm are shown in **Fig. 4**. Four modes can be seen at 635 nm, and one at 1550 nm. Number and positions of dark lines correspond to our calculations published recently [14].

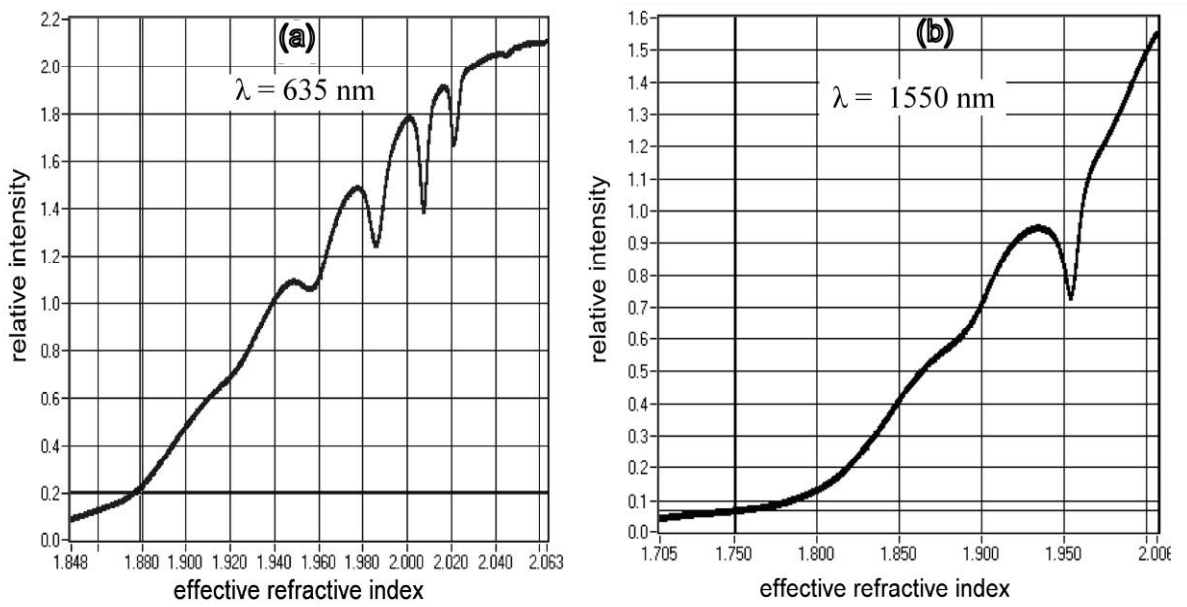


Fig.4 M-line spectra of waveguide in Er: Te glass. Fluence = $8 \cdot 10^{16}$ ions/cm^2, E =3.5 MeV. (a) at 635 nm and (b) at 1550 nm.

Instead of presenting the measured effective refractive indices in tables, their dependence on the irradiating fluence will be shown in some figures. Effective refractive index of the fundamental mode as a function of the irradiating fluence at both 1.5 and 3.5 MeV energy is presented in **Fig. 5**.

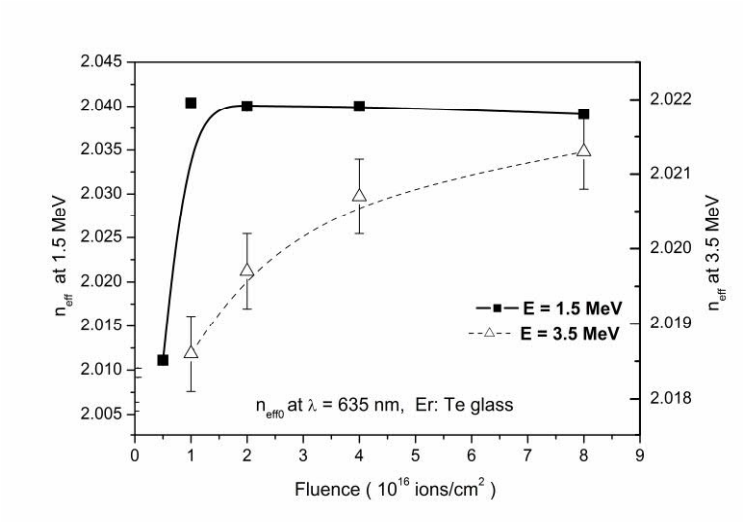


Fig.5 Effective refractive index of the fundamental mode *vs.* fluence at λ = 635 nm for 1.5 MeV (full squares) and 3.5 MeV (open triangles), Er: Te glass. Note the different abscissas for the two curves.

There is a large change of 0.03 in n_{eff0} between $0.5 \cdot 10^{16}$ and $1 \cdot 10^{16}$ ions/cm^2 in the 1.5 MeV curve, a clear indication of the onset of guiding in higher modes. Only a slow increase of n_{eff0} can be observed at the 3.5 MeV curve. (Note that no irradiation was performed at 3.5 MeV under the fluence of $1 \cdot 10^{16}$ ions/cm^2.) Effective refractive index of the first mode as a function of the irradiating fluence at both 1.5 and 3.5 MeV energy is presented in **Fig. 6**. Only very small changes of a few thousands in n_{eff1} can be observed at both 1.5 and 3.5 MeV. The effective refractive index seems to increase monotonically at 1.5 MeV while it passes apparently through a maximum at 3.5 MeV.

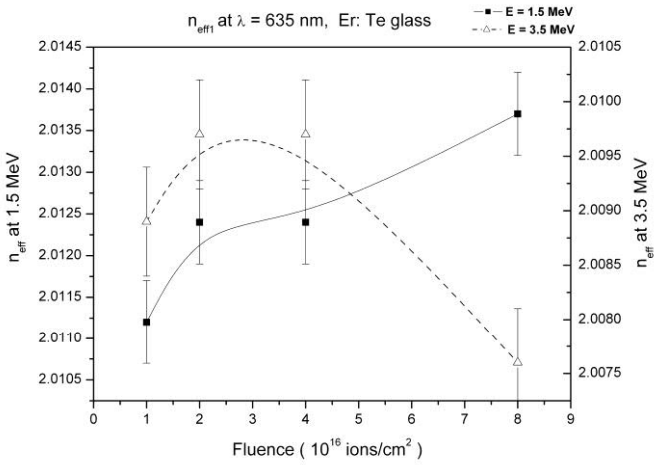


Fig.6 Effective refractive index of the first mode *vs.* fluence at $\lambda = 635$ nm for 1.5 MeV (full squares) and 3.5 MeV (open triangles), Er: Te glass. Note the different abscissae for the two curves.

5.2 Results for BGO crystals

Waveguides written in both types of BGO crystals supported guiding modes (in TE polarisation) up to $\lambda = 1310$ nm in the fluence range between $2 \cdot 10^{15}$ and $1.6 \cdot 10^{16}$ ions/cm^2. However, only waveguides written in Eulytine type BGO worked at 1550 nm. Fundamental mode was supported in the whole range of irradiated fluence, while first mode was detected only in waveguides irradiated with fluences of $0.8 \cdot 10^{16}$ and $1.6 \cdot 10^{16}$ ions/cm^2. M-line spectra,

taken at 635 and 1550 nm, of a waveguide irradiated with $1.6 \cdot 10^{16}$ ions/cm^2 are shown in **Fig. 7**

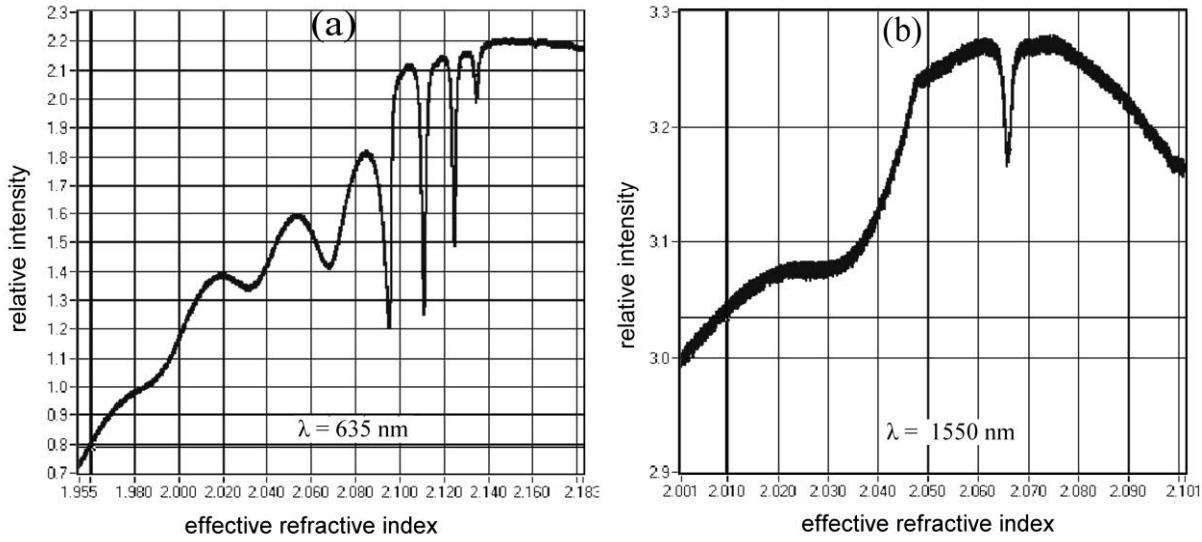


Fig.7 M-line spectra of waveguide in Eulytine BGO. Fluence = $1.6 \cdot 10^{16}$ ions/cm^2, E =3.5 MeV. (a) at 635 nm and (b) at 1550 nm.

Six mode can bee seen in the 635 nm m-line spectrum, while only two at 1550 nm. Effective refractive index of the fundamental mode, n_{eff0} *vs.* fluence of the BGO waveguides, measured at 635 nm, can be seen in **Fig. 8.**

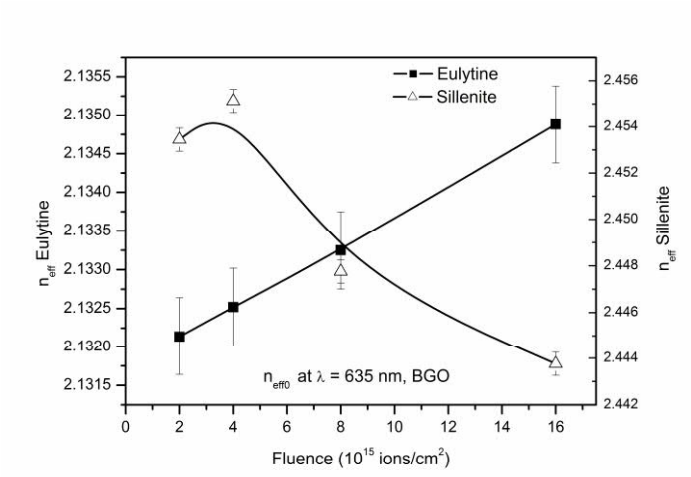


Fig.8 Effective refractive index of the fundamental mode *vs.* fluence at λ = 635 nm for waveguides in Eulytine (full squares) and Sillenite (open triangles) BGO crystals Note the different abscissas for the two curves.

A quasi-linear increase of n_{eff0} can be seen for waveguides written in Eulytine BGO, while it has a decreasing trend for Sillenite BGO. However, n_{eff0} of waveguides in Sillenite type BGO has a different trend at 980 nm, as seen in **Fig. 9**.

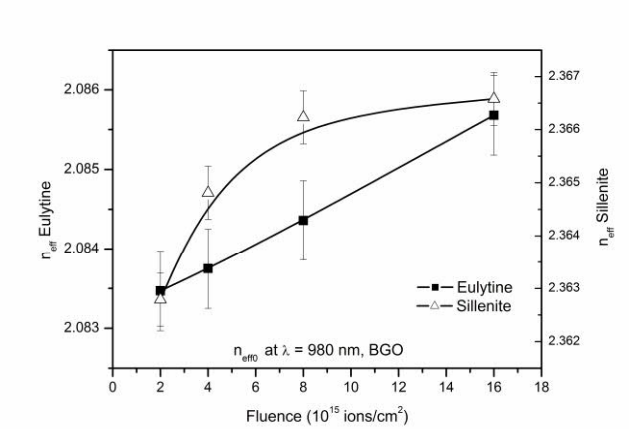


Fig.9 Effective refractive index of the fundamental mode *vs.* fluence at λ = 980 nm for waveguides in Eulytine (full squares) and Sillenite (open triangles) BGO crystals Note the different abscissas for the two curves.

The effective refractive index of the first mode, n_{eff1} *vs.* fluence curves for the two types of BGO crystal are very similar to the corresponding n_{eff0} *vs.* fluence curves.

6. Conclusion

Slab waveguides were fabricated in an erbium - doped tungsten tellurite glass and in two optical single crystals, using single- and double energy irradiation with MeV energy N^+ ions. Energy of the implanted N^+ ions was between 1.5 MeV and 3.5 MeV. Fluences of the implanted ions ranged from 5 x 10^{12} to 8 x 10^{16} ions/cm^2. M-line spectroscopic study of the samples revealed that the waveguides in these materials were of optical barrier type, where the implanted layer had a reduced index of refraction with respect to the nonimplanted bulk material, and the layer between the sample surface and the implanted ion range acted as a well. Beginning from an implanted fluence of 5 x 10^{14} ions/cm^2, modes could be detected with m-line spectroscopy in all tellurite glass waveguides. Saturation of the refractive index

change occurred in the $5 \cdot 10^{16} - 10^{17}$ ions/cm^2 range of implanted fluence. Modes were detected at 1550 nm, too in waveguides implanted with N^+ ions of 3.5 MeV energy and at double-energy at 3.5 + 3.0 MeV and 3.5 + 2.5 MeV.

It has been proved that irradiation with 3.5 MeV N^+ ions could also be used for producing planar waveguides in both types of BGO crystals: $Bi_4Ge_3O_{12}$ (eulytine) and $Bi_{12}GeO_{20}$ (sillenite). Modes could be observed up to 1550 nm in waveguides written in $Bi_4Ge_3O_{12}$, and up to 1310 nm in those written in $Bi_{12}GeO_{20}$.

Spectroscopic ellipsometric measurements essentially confirmed the results obtained in the m-line tests. Fitting ellipsometric data with a three-layer model yielded a thin buried layer, centred at the range of the implanted ions. Thickness of the buried layer increased with increasing fluence, thus corroborating the results obtained with the m-line technique. However, refinement of the ellipsometric model is necessary. Development of a model based on whole set of m-line spectra measured at all the available wavelengths to reconstruct refractive index profile of the waveguides is under way. New sets of elongated planar waveguides have been irradiated in both Er: Te glass and BGO crystals to allow for propagation loss measurements. Besides of the double prism method, propagation losses will be measured by the back-reflection method, too. It is planned that guiding will be checked in all the suitable N^+ - irradiated samples by end-face coupling. Experiments with thermal annealing of the irradiated waveguides to improve their quality will be carried out in the near future.

Acknowledgements

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Table and Figure Captions

Table 1. Summary of the implantation energies and fluences for all the waveguides

Table 2. Results of spectroscopic ellipsometric measurements of Er: tellurite glass waveguides

Table 3. Results of spectroscopic ellipsometric measurements of BGO waveguides

Fig. 1. Interference phase contrast microscopic image of channel waveguides implanted in an Er: Te glass sample. The fluences were 0.5, 1, 2, and $4x10^{16}$ ions/cm^2 in stripes A, B, C, and D. Conventional optical microscopic image of stripe B is also shown in the inset.

Fig. 2. SRIM simulation and SE fit of the waveguide structure in Er: Te glass at various irradiation energies and fluences: **a)** E = 1.5 MeV, fluences are $1 \cdot 10^{16}$ and $4 \cdot 10^{16}$. **b)** E = 3.5 MeV, fluences are $1 \cdot 10^{16}$ and $8 \cdot 10^{16}$ ions/cm^2. **c)** E = 3.5 MeV + 3.0 MeV, fluence is $4 \cdot 10^{16}$ ions/cm^2.

Fig. 3 SRIM simulation and SE fit of the waveguide structure in BGO with 3.5 N^+ irradiation at various fluences: **a)** Eulytine, fluences are $0.2 \cdot 10^{16}$ and $1.6 \cdot 10^{16}$. **b)** Sillenite, fluences are $0.2 \cdot 10^{16}$ and $1.6 \cdot 10^{16}$ ions/cm^2.

Fig.4 M-line spectra of waveguide in Er: Te glass. Fluence = $8 \cdot 10^{16}$ ions/cm^2, E =3.5 MeV. (a) at 635 nm and (b) at 1550 nm.

Fig.5 Effective refractive index of the fundamental mode *vs.* fluence at λ = 635 nm for 1.5 MeV (full squares) and 3.5 MeV (open triangles), Er: Te glass. Note the different abscissas for the two curves.

Fig.6 Effective refractive index of the first mode *vs.* fluence at λ = 635 nm for 1.5 MeV (full squares) and 3.5 MeV (open triangles), Er: Te glass. Note the different abscissas for the two curves.

Fig.7 M-line spectra of waveguide in Eulytine BGO. Fluence = $1.6 \cdot 10^{16}$ ions/cm^2, E =3.5 MeV. (a) at 635 nm and (b) at 1550 nm.

Fig.8 Effective refractive index of the fundamental mode *vs.* fluence at λ = 635 nm for waveguides in Eulytine (full squares) and Sillenite (open triangles) BGO crystals Note the different abscissas for the two curves.

Fig.9 Effective refractive index of the fundamental mode *vs.* fluence at λ = 980 nm for waveguides in Eulytine (full squares) and Sillenite (open triangles) BGO crystals Note the different abscissas for the two curves.

Table 1

Table 1. Summary of the implantation energies and fluences for all the waveguides

		Names of the waveguides and implanted fluences ($x10^{15}$ ions/cm^2)							
Name of the target	N+ energy (MeV)	A	B	C	D	E	F	G	H
Er: Te glass	1,5	0.005	0.05	0.5	5	10	20	40	80
Er: Te glass	3.5	10	20	40	80	-	-	-	-
Er: Te glass, 2 energy	3.5, 3.5+3.0, 3.5+2.5	40	40	40					
$Bi_4Ge_3O_{12}$	3.5	2	4	8	16	-	-	-	-
$Bi_{12}GeO_{20}$	3.5	2	4	8	16	-	-	-	-

Table 2

Table 2. Results of spectroscopic ellipsometric measurements of Er: tellurite glass waveguides

N+ energy (MeV)	1.5				3.5			
Names of the waveguides	E	F	G	H	A	B	C	D
Fluences ($x10^{16}$ ions/cm^2)	1	2	4	8	1	2	4	8
Thickness of $layer_2$ [nm]	1781 ± 19	1785 ± 28	1779 ± 16	-	2615.1 ± 1.6	2643.6 ± 14.5	2403.8 ± 5.1	2384.7 ± 4.6
Refractive index of $layer_2$ at 635 nm	2.052	2.048	2.052	-	2.063	2.042	2.040	2.097
Refractive index of $layer_2$ at 1550 nm					1.984	1.965	1.969	1.962
Thickness of $layer_1$ [nm]	67 ± 22	83 ± 35	97 ± 19	-	183.4 ± 9.8	195.8 ± 4.6	457.3 ± 4.7	489.8 ± 8.6
Refractive index of $layer_1$ at 635 nm	2.071	2.068	2.071	-	2.014	2.025	2.070	2.004
Refractive index of $layer_1$ at 1550 nm					1.954	1.955	1.936	1.960
Refractive index of the non-implanted glass at 635 nm	2.081	2.081	2.081	-	2.019	2.019	2.019	2.019
Refractive index of the non-implanted glass at 1550 nm					1.950	1.950	1.950	1.950

Table 3

Table 3. Results of spectroscopic ellipsometric measurements of BGO waveguides

BGP crystal type	$Bi_4Ge_3O_{12}$				$Bi_{12}GeO_{20}$			
Names of the waveguides	A	B	C	D	A	B	C	D
Fluences ($x10^{16}$ ions/cm^2)	0.2	0.4	0.8	1.6	0.2	0.4	0.8	1.6
Thickness of $layer_2$ [nm]	2552.7 ± 0.9	2575.8 ± 1.1	2632.9 ± 0.9	2628.1 ± 0.8	2500.2 ± 21.6	2571.6 ± 3.1	2588.2 ± 3.1	2685.7 ± 1.70
Refractive index of $layer_2$ at 635 nm	2.115	2.130	2.109	2.125	2.393	2.380	2.382	2.368
Refractive index of $layer_2$ at 1550 nm	2.065	2.068	2.058	2.063	2.333	2.3	2.358	2.330
Thickness of $layer_1$ [nm]	337.9 ± 10.6	287.9 ± 2.9	346.4 ± 4.2	412.9 ± 4.6	294.9 ± 42.5	517.9 ± 19.5	472.8 ± 27.4	348.2 ± 9.2
Refractive index of $layer_1$ at 635 nm	2.087	2.086	2.085	2.088	2.370	2.549	2.467	2.650
Refractive index of $layer_1$ at 1550 nm	2.041	2.037	2.038	2.035	2.418	2.308	2.395	2.26
Refractive index of the non-implanted glass at 635 nm	2.085	2.085	2.085	2.085	2.487	2.487	2.487	2.487
Refractive index of the non-implanted glass at 1550 nm	2.049	2.049	2.049	2.049	2.410	2.410	2.410	2.410

Figure 1

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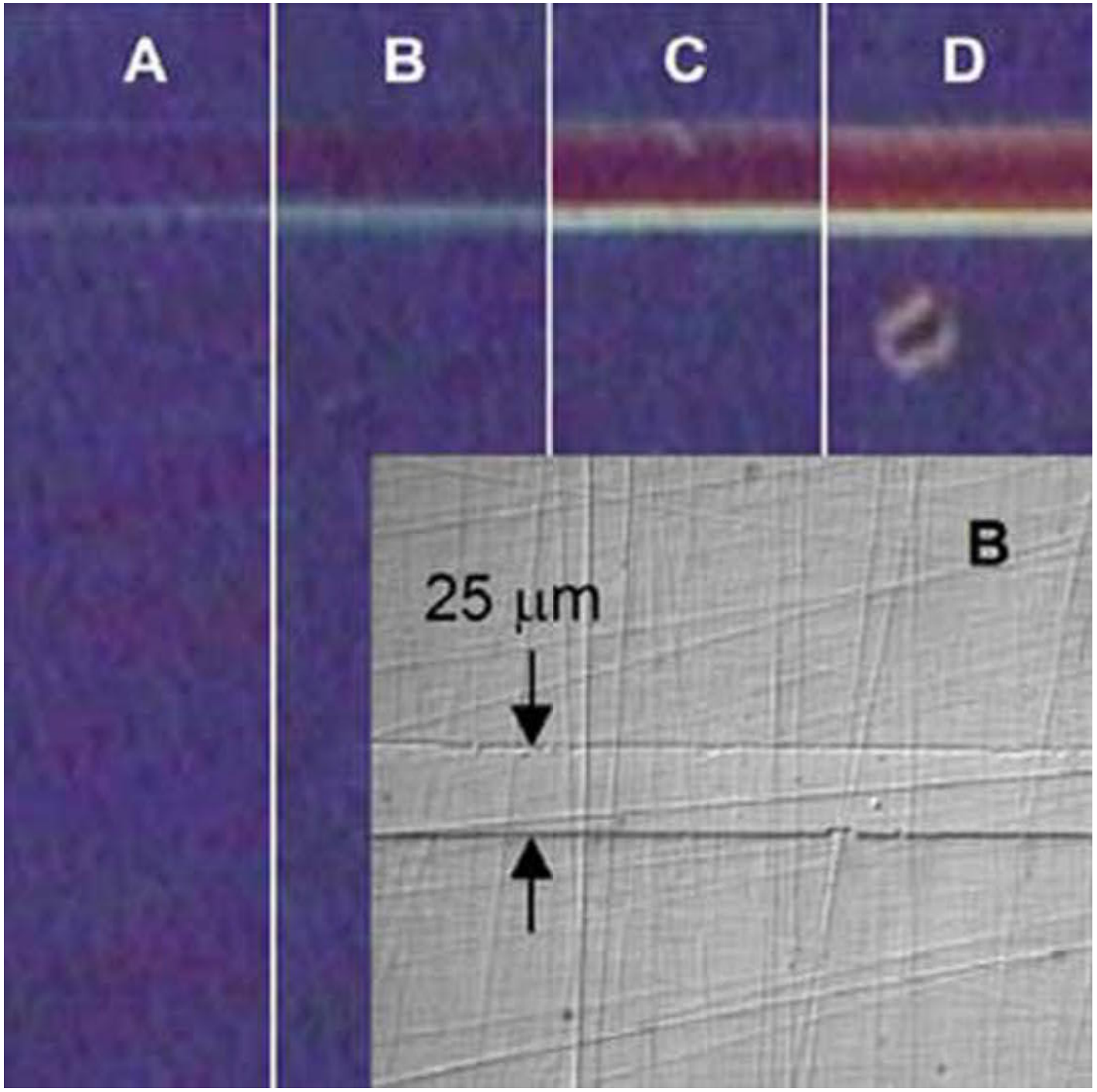

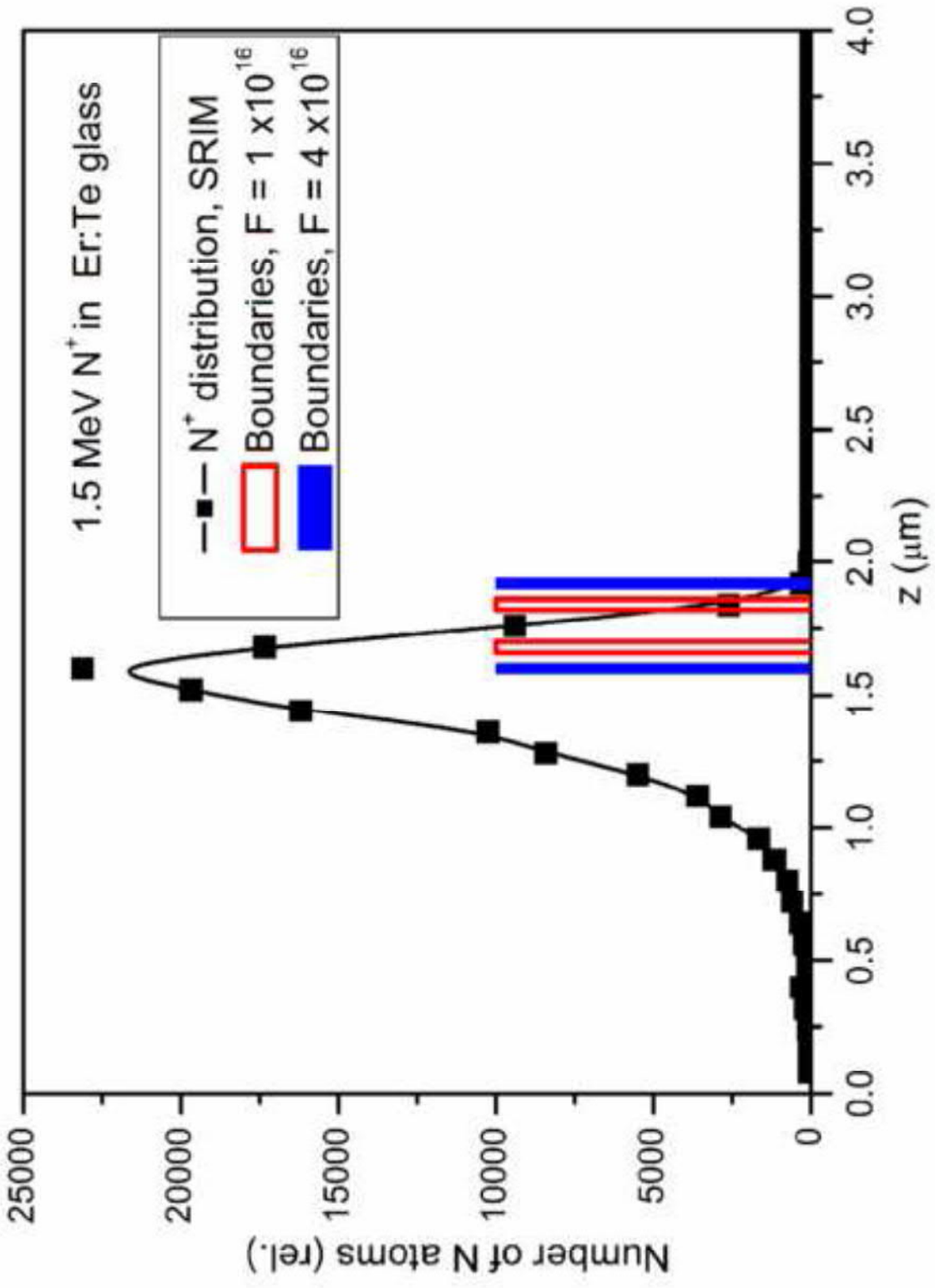

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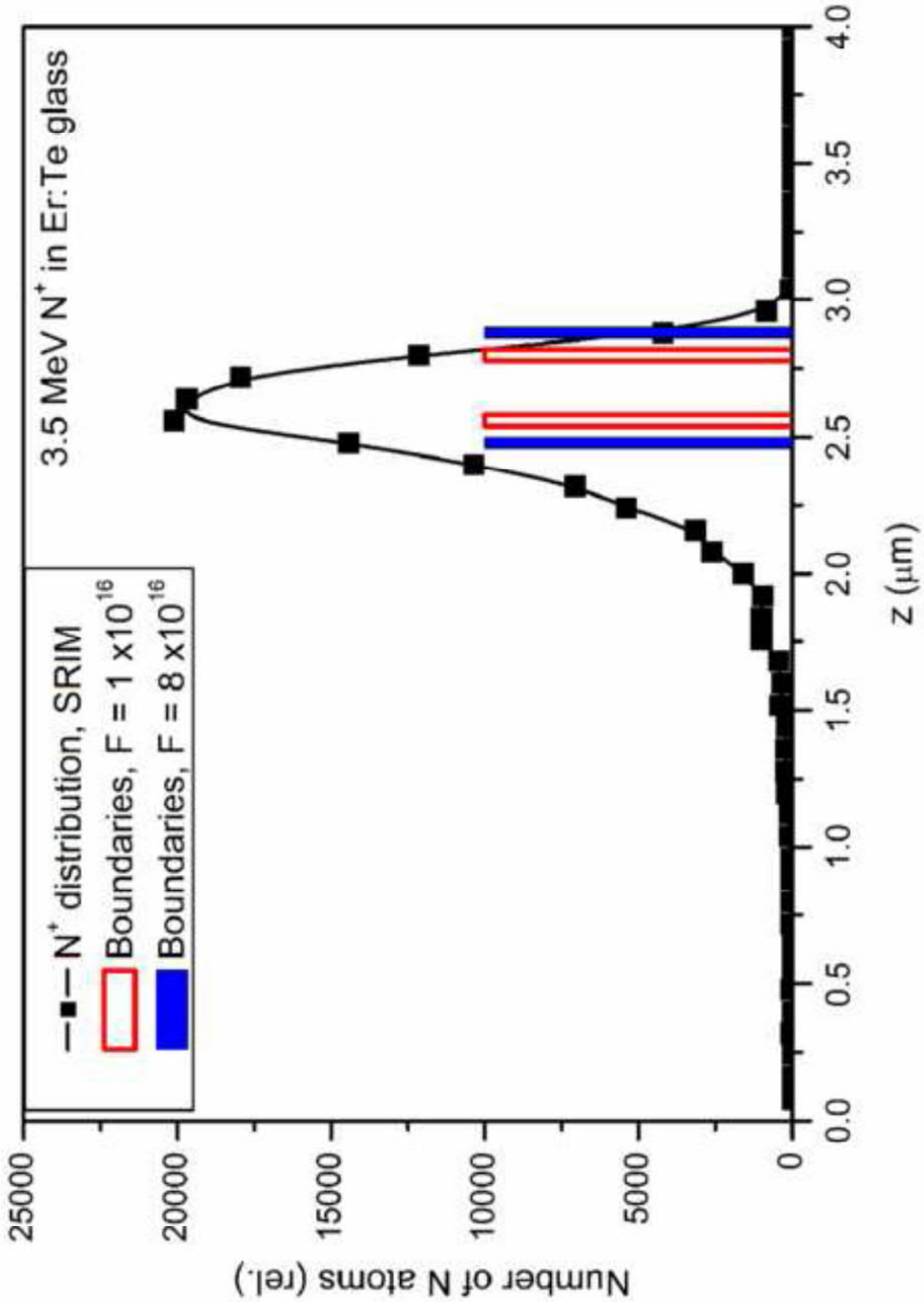

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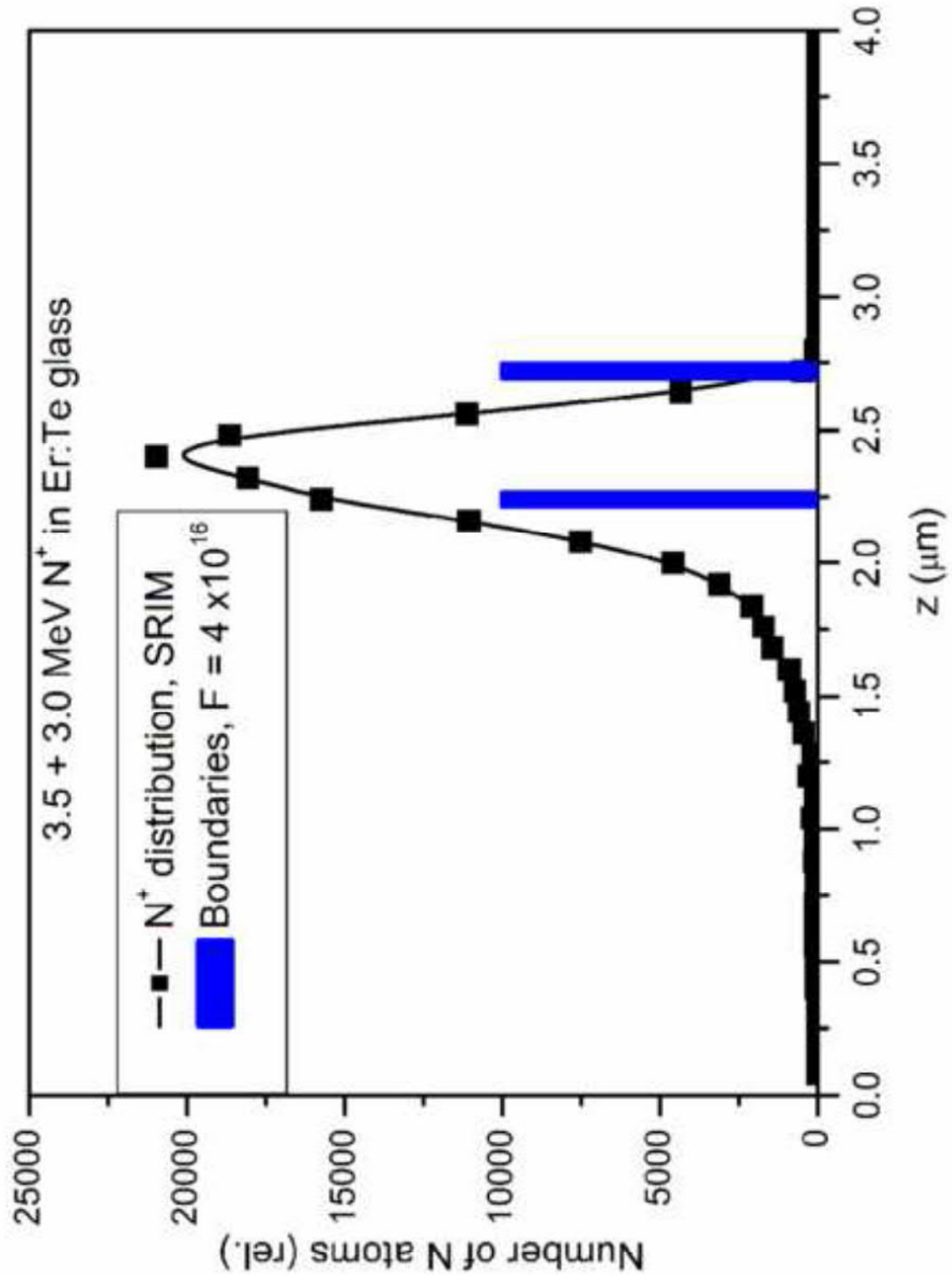

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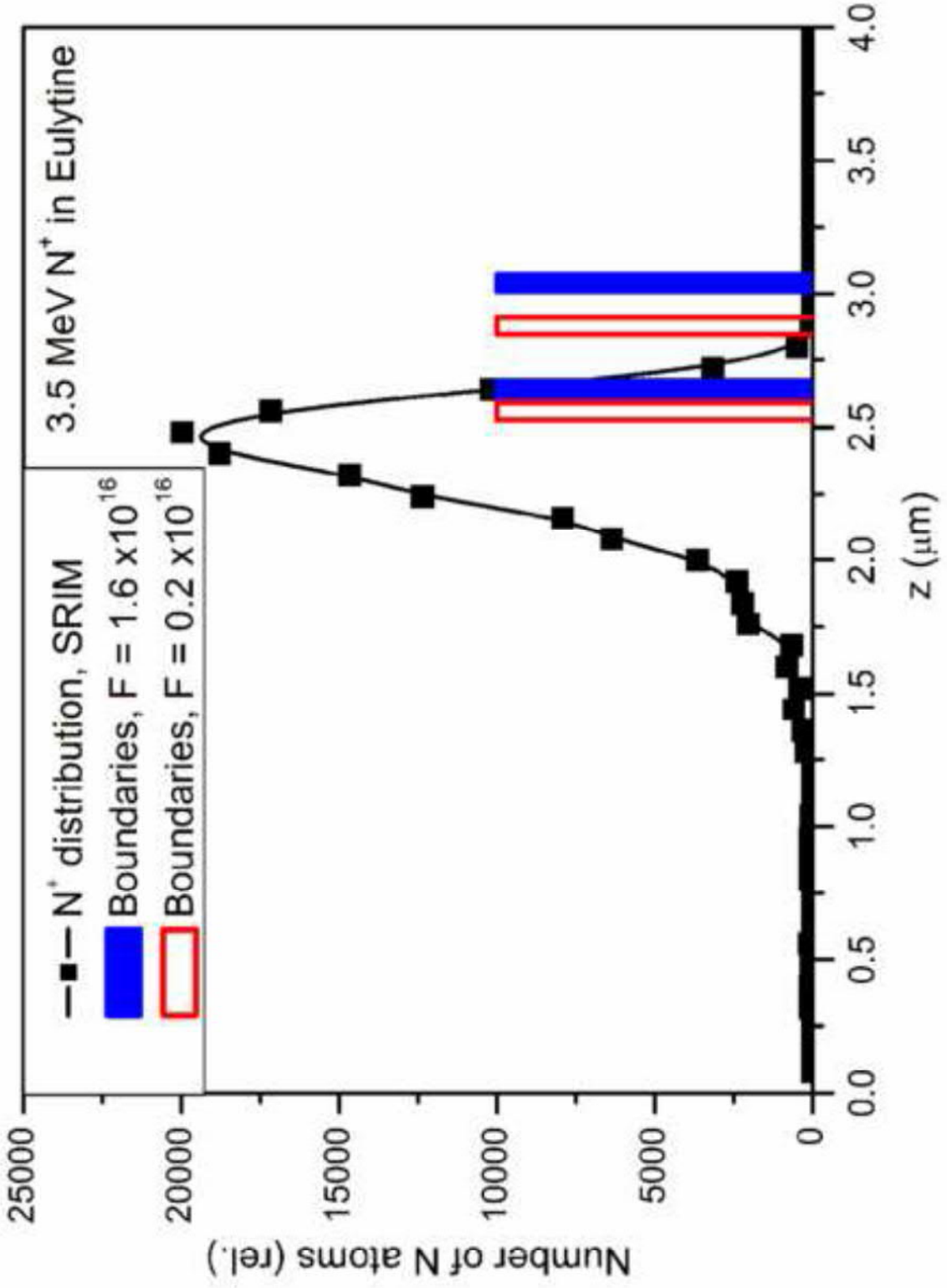

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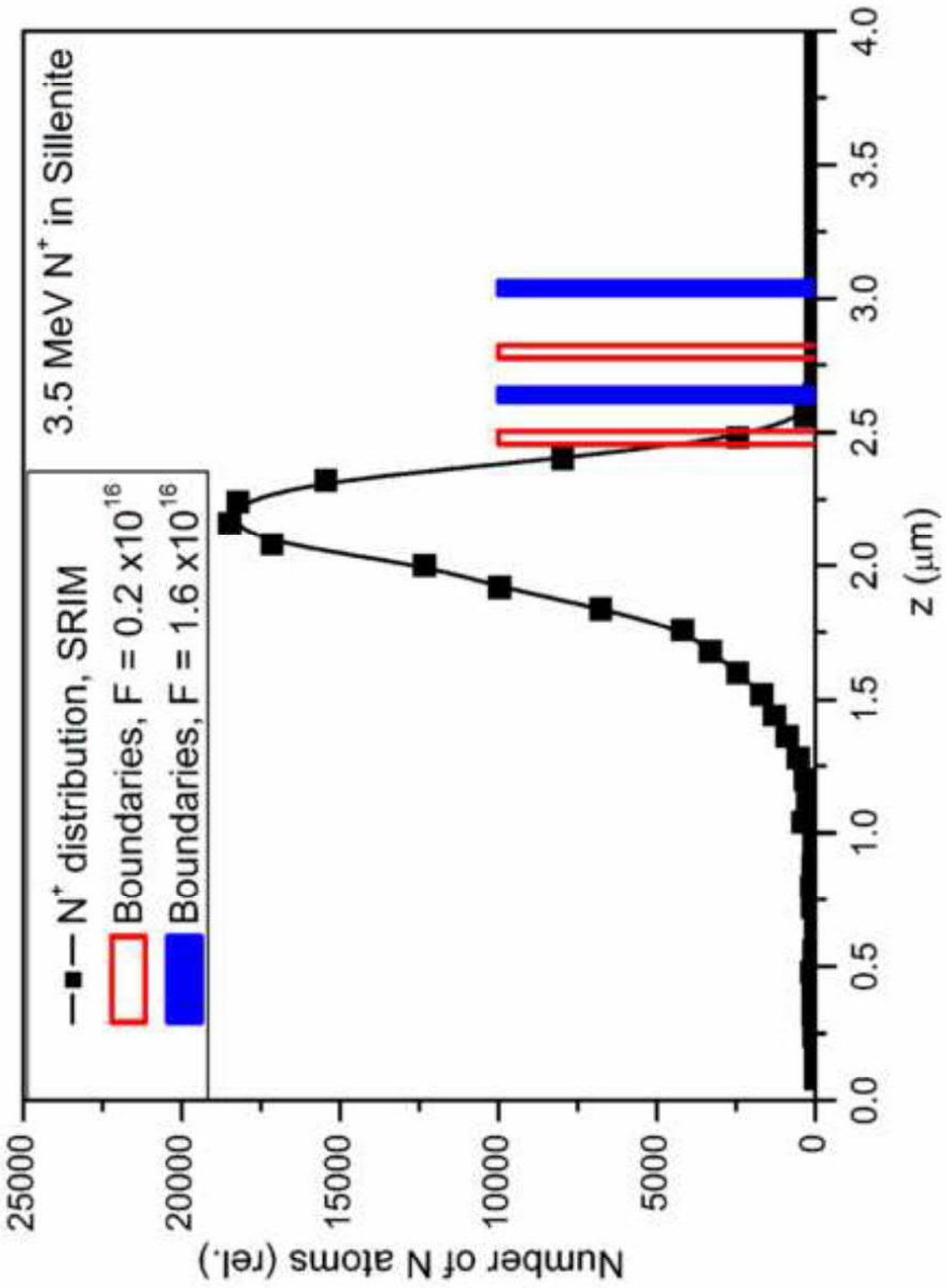

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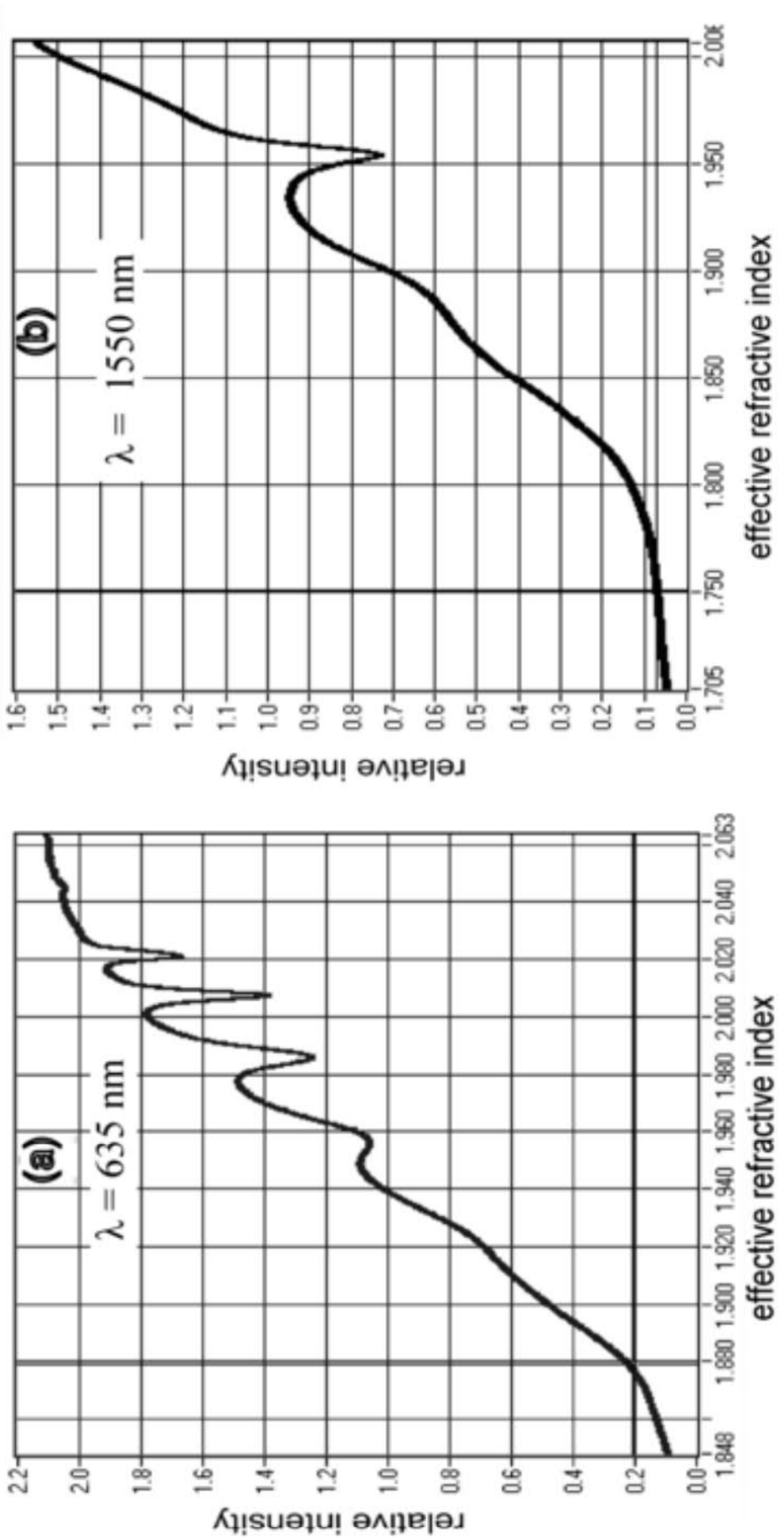

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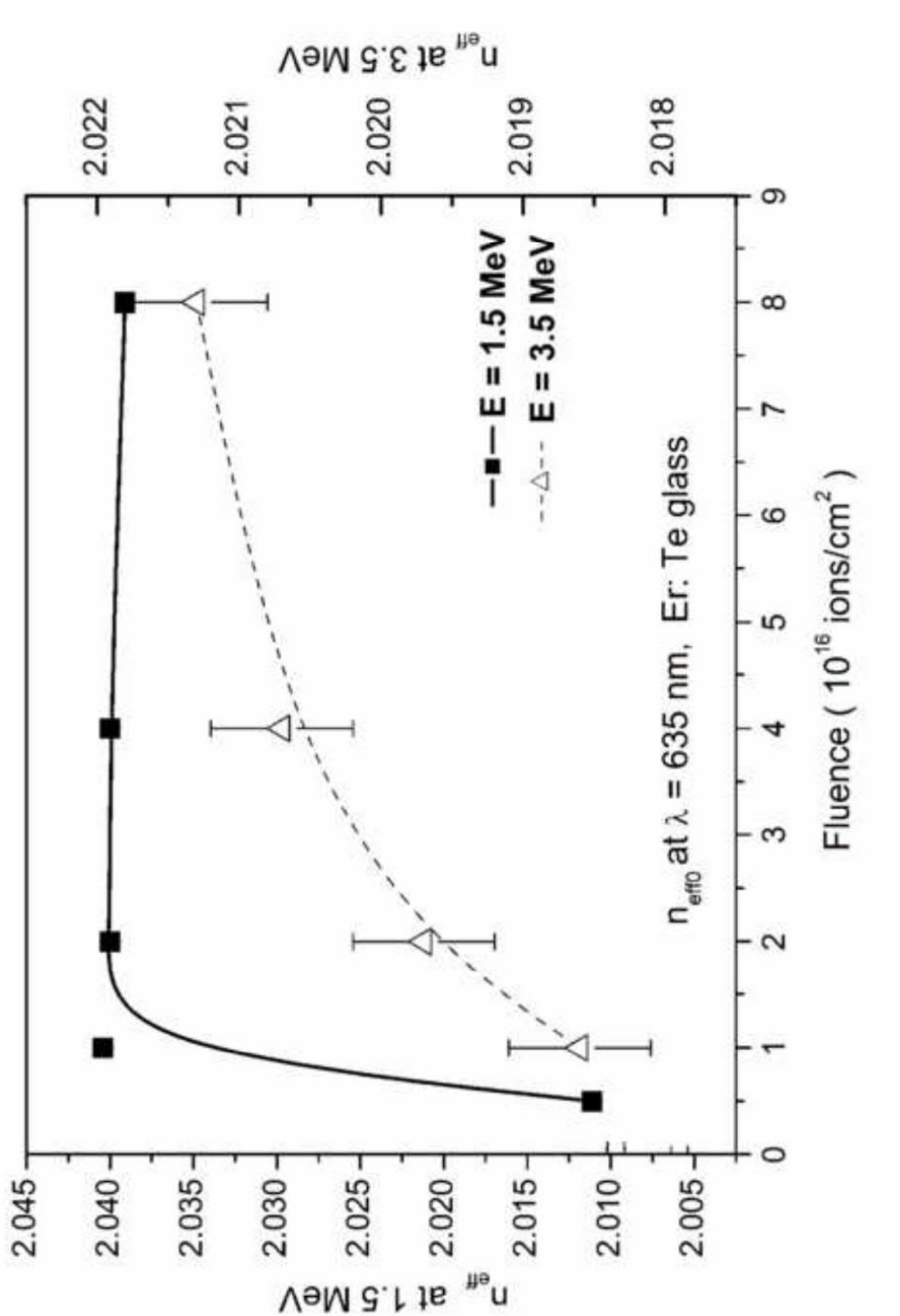

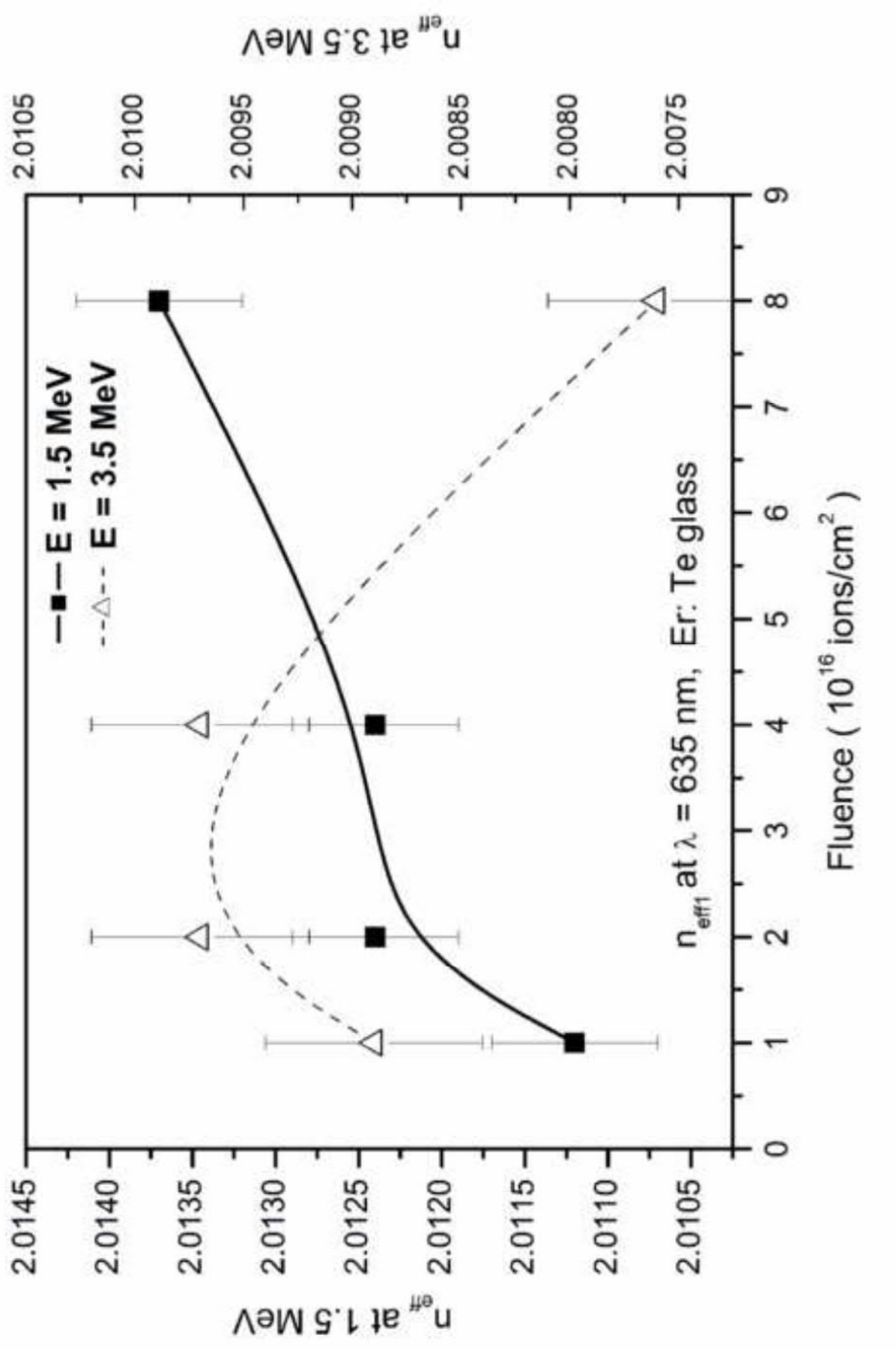

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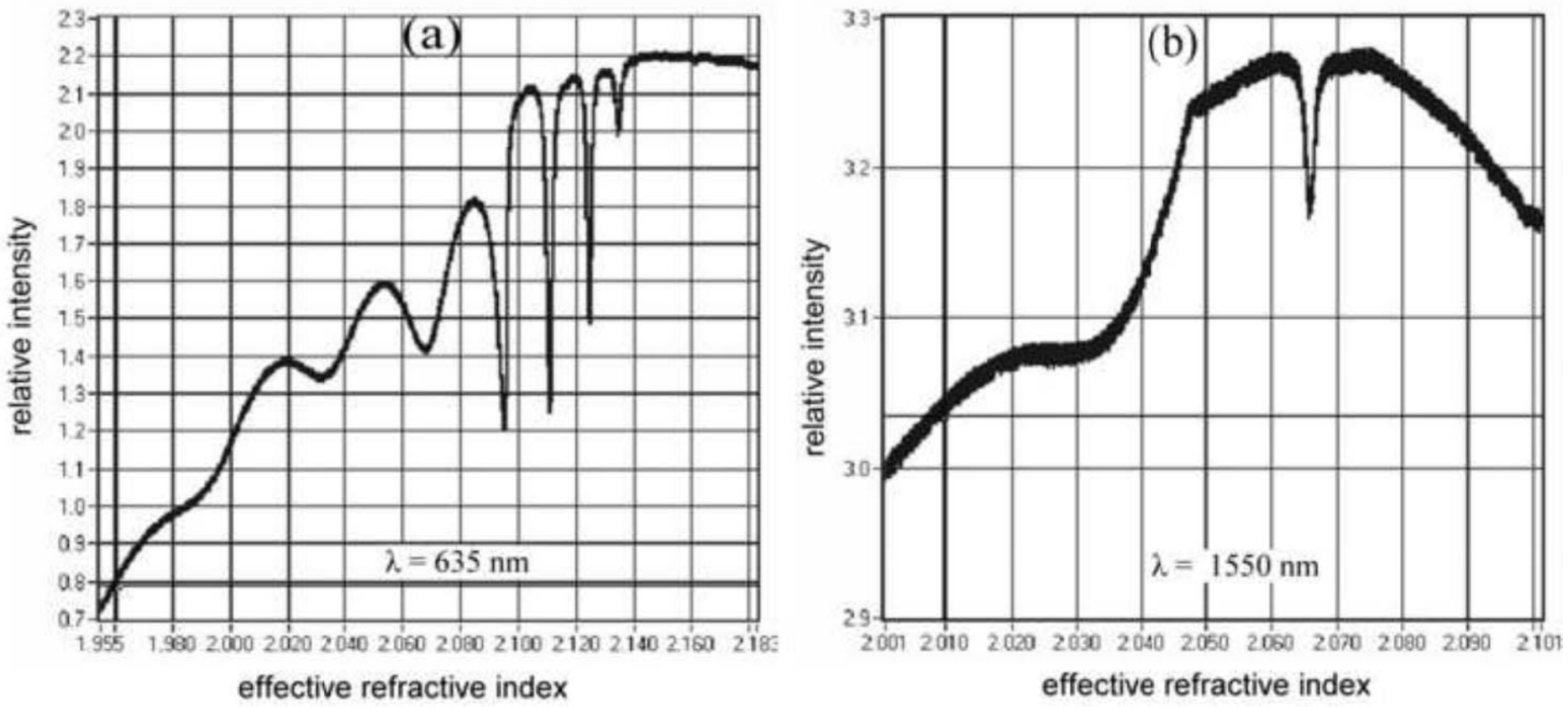

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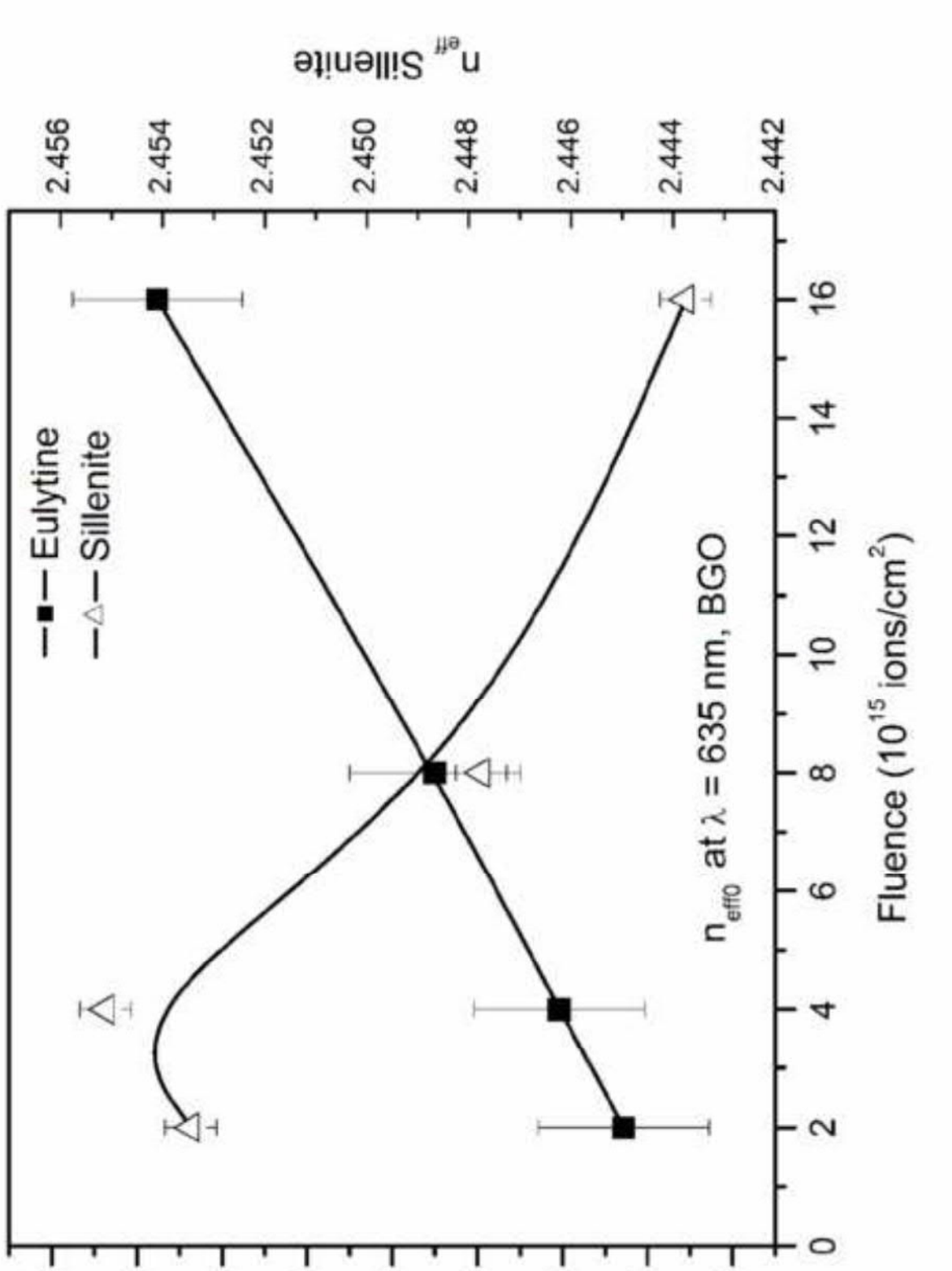

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