KFKI-1982-105

T. LOHNER
G. MEZEY
E. KÓTAI
F. PÁSZTI
A. MANUABA
J. GYULAI

CHARACTERIZATION OF ION IMPLANTED SILICON BY ELLIPSOMETRY AND CHANNELING EFFECT

Hungarian Academy of Sciences

**CENTRAL
RESEARCH
INSTITUTE FOR
PHYSICS**

BUDAPEST

KFKI-1982-105

CHARACTERIZATION OF ION IMPLANTED SILICON BY ELLIPSOMETRY AND CHANNELING EFFECT

T. Lohner, G. Mezey, E. Kótai, F. Pászti,
A. Manuaba and J. Gyulai

Central Research Institute for Physics
H-1525 Budapest 114, P.O.B. 49, Hungary

Presented at the International Conference on Ion Beam Modification of Materials, Grenoble, 6-10 September, 1982;

Submitted to Nuclear Instruments and Methods

HU ISSN 0368 5330
ISBN 963 372 020 6

ABSTRACT

A correlation between the amount of disorder measured by channeling and the trajectory of measured ellipsometric angles (ψ,Δ) is reported. The implantation was performed by $^{11}B^+$, $^{28}Si^+$, $^{31}P^+$, $^{40}Ar^+$, $^{72}Ge^+$, $^{75}As^+$, $^{209}Bi^+$ ions at room temperature. For fully amorphous samples the thickness data were obtained from channeling and the complex refractive index originated from a 145 nm thick amorphous layer. These experimental values were used to compute a theoretical curve in the ψ-Δ plane. The good agreement between the theoretical curve and experimental data provides a non-destructive, rapid and non-contact method to estimate the thickness of the amorphous layer.

For buried and partially disordered layers a qualitative interpretation of different trajectories depending on the ion species and other implantation condition such as energy and dose in the ψ-Δ plane can be given on the basis of channeling measurements in certain cases. It is also pointed out that plasma stripping plays an important role in preparing implanted samples for ellipsometry by removing the polymerized hydrocarbon film without affecting the disordered layer.

АННОТАЦИЯ

Методами обратного резерфордовского рассеяния, комбинированным с эффектом каналирования, и эллипсометрии исследовались радиационные повреждения и осаждение углеводородов на кремниевых кристаллах, вызванные ионной имплантацией.

Комплексный показатель преломления аморфной кремниевой пленки был определен по углам Ψ и Δ, измеренным эллипсометром, и по толщине пленки, измеренной при помощи эффекта каналирования. Кривые в плоскости Ψ-Δ, полученные путем моделирования с ЭВМ на основе четырехфазной оптической модели, сравнивались со значениями, измеренными на имплантированных образцах. В случае полностью аморфных пленок экспериментальные данные хорошо согласуются с теоретической кривой. Для качественной интерпретации измеренных значений Ψ и Δ в случае частично разрушенных слоев значительную помощь оказали измерения эффекта каналирования.

KIVONAT

Csatornahatással kombinált Rutherford-visszaszórással és ellipszometriával vizsgáltuk az ionimplantáció által okozott sugárzási károsodást és hidrokarbon lerakódást sziliciumkristályokon.

Az amorf sziliciumréteg komplex törésmutatoját az ellipszométerrel mért ψ- és Δ-szögek és a csatornahatással mért rétegvastagság alapján határoztuk meg. A négyfázisu optikai modell alapján a ψ-Δ sikon számitógépes szimulációval készitett görbéket összehasonlitottuk az implantált mintákon mért értékekkel. Teljesen amorf rétegek esetén jó az egyezés a kisérleti adatok és az elméleti görbe között. Részlegesen roncsolt rétegek esetében a mért ψ- és Δ-értékek kvalitativ interpretálásához lényeges segitséget nyujtottak a csatornahatáson alapuló mérések.

1. INTRODUCTION

During ion irradiation of a semiconductor sample a considerable amount of damage is produced in the substrate as the ion comes to rest. A variety of techniques such as transmission electron microscopy (TEM) [1,2], backscattering spectrometry (BS) [3,4], optical reflection and transmission spectroscopy [5,6], electron paramagnetic resonance (EPR) [7,8] have been employed to obtain information upon the damaged region.

Apart from these methods there is the technique of ellipsometry, which is a sensitive, rapid and non-contact method of characterizing surface layers of materials [9,10] enabling changes in the state of polarized light after reflection to be studied. In addition ellipsometry has been proved to be a powerful means of investigating ion-bombarded layers [11-27].

For disorder analysis the combination of high resolution channeling [28, 29] with ellipsometry after appropriate surface cleaning [23] seems to be promising [24].

In this paper we emphasize the important parameters that contribute to the measured ellipsometric data on ion-implanted silicon. We also deal with the results of measurements of damage thickness and the degree of disorder on ion-implanted silicon by combining ellipsometry with channeling.

2. EXPERIMENTAL

For experiments single crystal silicon wafers of both <111> and <100> orientation were used. As the cleanliness of the surface is a crucial point for optical studies Wacker-made wafers were placed into an implantation machine without any additional surface cleaning.

To produce disordered layers, three sets of implantations were done at room temperature. The first set was performed by 40 keV $^{11}B^+$ in the dose range of 1.6×10^{15}-1×10^{16} atoms/cm^2. In the second case, the thickness of the amorphized layers was varied between 42 and 150 nm using energies of 30-80 keV and different types of ions. Table 1 summarizes the implantation conditions. The shape of disorder distribution and the thickness of the amorphous layers were measured by channeling of 5 nm resolution using glancing detection [28,29].

The third set of implantations was performed by 60 keV $^{31}P^+$ ions in the dose range of 3×10^{13}-3×10^{15} atoms/cm^2.

A Soviet-made manual apparatus (type LEM-2) in the polarizer-compensator-sample-analyser (PCSA) configuration was used for ellipsometric measurements. The wavelength was 632.8 nm, and the ellipsometric angles were measured for an angle of incidence $\varphi = 70^{\circ}$.

3. RESULTS AND DISCUSSION

3.1 Disturbing effect of carbon build-up in the ellipsometric studies of ion-implanted silicon

Surface contamination of silicon produced by ion-implantation is due to the residual hydrocarbon gas pressure in the target chamber of the implantation machine. There have been few studies on carbon build-up by ion-induced polymerization [30-33].

We detected the presence of carbon contamination by backscattering spectrometry on boron implants where the relatively high dose implantation produces only a small amount of disorder consequently lower dechanneling at the energy of carbon. As an example 40 keV $^{11}B^{+}$ implantation into silicon with dose of 1×10^{16} atoms/cm^2 is shown here in *Fig. 1.* This figure illustrates the greatly improved depth resolution obtained using the glancing exit technique. The peak labelled "C" clearly shows the carbon contamination on the surface of the sample. Plasma stripping has proved to be an effective method of eliminating polymerized hydrocarbon molecules from the surface [23]. The channeling spectrum of plasma-stripped sample demonstrates the effectivity of this cleaning procedure.

Figure 2 shows the change of ellipsometric parameters as a function of duration of plasma stripping. The ψ parameter is only slightly affected, but a dramatic change can be observed in the Δ values. Such measurements have helped us in the optimization of plasma stripping procedure.

The dose dependence of ellipsometric parameters before and after plasma stripping is illustrated in *Fig. 3.* We can see that the higher the dose, the larger the difference between the data measured on as-implanted and plasma-stripped samples, respectively; so this carbon build-up disturbs the ellipsometric measurements especially at high doses. It is emphasized that plasma stripping is an important procedure in preparing ion-implanted samples for ellipsometry in that it removes the polymerized film without affecting the disordered layer.

3.2 Effect of thickness of amorphous layer

It has been shown that ellipsometry can be converted to a quantitative method for fast disorder analysis as long as the disordered layer is fully amorphous, i.e. optically homogeneous, and the implantation dose is not too high [24].

In this paragraph we offer further illustrative examples over a range of incident ions from $^{28}Si^+$ to $^{209}Bi^+$. *Figure 4* shows the measured ellipsometric parameters together with a computer-simulated theoretical spiral curve. The free parameter for simulation purposes was the thickness of the homogeneous amorphous layer. In the present simulations a four-phase approximation (air, 1 nm SiO_2, amorphous silicon layer of different thickness and single crystal bulk) was applied using a computer program published by McCrackin [34]. The respective complex refractive indices were $n_{ox}=1.45-0.001i$, $n_{amorph.}=4.63-0.76i$ and $n_{cryst.}=3.85-0.02i$. The optical constants of the amorphous silicon layer were determined by choosing an arsenic implanted silicon sample (130 keV As^+, 1×10^{15} atoms/cm^2) and applying the three phase model. The three phases refer to the air, the amorphous silicon layer of 145 nm thickness (determined by high depth resolution channeling measurement), and the crystalline silicon substrate.

Figure 4 illustrates that the measured ellipsometric values are in good agreement with the calculated ones and there is good agreement between the thickness data obtained by channeling and those from the above mentioned computer simulation. With these agreements we have a non-destructive, rapid, non-contact method estimating the thickness of amorphous layers.

3.3 Effect of ion-implantation dose

The effect of disorder production as a function of increasing dose for $^{11}B^+$ and $^{31}P^+$ implantation was investigated. *Figure 5* shows the measured ellipsometric parameters in the case of boron implanted samples. For comparison the starting part of a calculated spiral curve has been plotted. During the present calculations a four phase approximation was applied. Similarity was found in the behaviour of the theoretical and experimental trajectories. At first glance it seems that this similarity is surprising because the disorder distribution of the model is characterized by a rectangular, homogeneous shape but the channeling spectrum of boron implanted silicon (*Fig. 1*) shows an inhomogeneous disorder distribution.

A qualitative interpretation of this similarity can be given on the basis of the channeling spectra shown in *Fig. 1.* The energetic boron ions are shown to have generated substantial disorder near the surface of the silicon and created a buried disorder peak at a depth of approximately 130 nm. Thompson et al. [35] have recently shown that the light ion induced disordering is particularly rapid near the silicon surface. Other authors [36, 37] have observed a well defined damage peak just below the surface of boron implants.

Because ellipsometry is extremely sensitive to surface layers the substantial surface disorder has a dominant effect on the ellipsometric parameters and the buried disorder has only a secondary effect because of the attenuation of light while traversing the near surface region.

Figure 6 shows channeling spectra of 60 keV $^{31}P^{+}$ implants. The characteristic features of these spectra are that as ion fluence increases, disorder also increases in a depth dependent way. Saturation is reached rapidly at the depth where the disorder production rate is largest. At 6×10^{14} atoms/cm^2 the channeling suggests that the buried disorder becomes fully amorphous, and at 1×10^{15} atoms/cm^2 the surface becomes fully amorphous, too. The thickness of this amorphous layer increases slowly with ion fluence and the amorphous-crystalline boundary moves slowly into the silicon.

The corresponding ellipsometric data with the theoretical spiral curve are shown in *Fig. 7*. For lower doses, where the damaged layer is optically inhomogeneous, the trajectory of the measured ellipsometric parameters exhibits a peculiar shape. For doses necessary for amorphization, the ellipsometric parameters follow the theoretical curve. There is a good agreement between thickness data obtained by channeling and the thickness values of the computer simulation.

It is a remarkable fact that a small increase in implantation dose in the region of 6×10^{14}-1×10^{15} atoms/cm^2 causes a drastic change in ψ which is correlated with the change of the degree of amorphousness at the surface region.

4. SUMMARY AND CONCLUSIONS

The monitoring of implantation induced disorder is an important task in the fabrication of integrated circuits. Ellipsometry is an attractive method for monitoring ion-implantation induced damage due to its non-contact and non-destructive nature and to its sensitivity and experimental simplicity. The quantitative determination of the complex refractive index changes due to ion-bombardment are complicated by the fact that for silicon the implanted sample has a multilayer structure: an underlying single-crystal substrate, the ion-implantation disordered layer, and a native oxide layer covering the disordered layer.

In conclusion, we have shown that the non-destructive ellipsometric method is sensitive to ion-implantation induced damage. Ion-implanted silicon has been approximated as a four-layer structure composed of air, the single-crystal silicon substrate, the implantation disordered layer, and a native oxide layer. We have demonstrated that this approximation is suitable for a fully amorphous layer. In the case of buried and partially disordered layers the channeling method helps to provide a qualitative interpretation of the measured ellipsometric parameters.

ACKNOWLEDGEMENT

We wish to thank G. Pető, P. Révész and A. Dévényi for helpful discussions. The authors are grateful to the staff of the Van de Graaff accelerator for their continuous cooperation. Implantations are acknowledged to the staff of implantation machines. Thanks are due to Mrs R. Majthényi for drawing the illustrations and to Mrs M. Baranyi for typing the manuscript.

REFERENCES

[1] D.J. Mazey, R.S. Nelson and R.S. Barnes, Phil. Mag. 17 (1968) 1145.

[2] D.K. Sadana, M. Stratham, J. Washburn and G.R. Booker, J. Appl. Phys. 51 (1980) 5718.

[3] W.K. Chu, J.W. Mayer and M.-A. Nicolet, Backscattering Spectrometry (Academic Press, New York, 1978)

[4] D.A. Thompson, A. Golanski, K.H. Haugen, D.V. Stevanovic, G. Carter and C.E. Christodoulides, Rad. Eff. 52 (1980) 69.

[5] E.C. Baranova, V.M. Gusev, Yu.V. Martynenko, C.V. Starinin and I.B. Khaibullin, Rad. Eff. 18 (1973) 21.

[6] K. Hehl and W. Wesch, phys. stat. sol. (a) 58 (1980) 181.

[7] N.N. Gerasimenko, Proc. Int. Conf. on Radiation Effects in Semiconductors, Dubrovnik, 1976 (Institute of Physics, 1977) 164.

[8] N.A. Sobolev, G. Götz, W. Karthe and B. Schnabel, Rad. Eff. 42 (1979) 23.

[9] R.M.A. Azzam and N.M. Bashara, Ellipsometry and Polarized Light (North-Holland, Amsterdam, 1977)

[10] A.V. Rzhanov and K.K. Svitashev, Advances in Electronics and Electron Physics, 49 (1979) 1.

[11] M.M. Ibrahim and N.M. Bashara, Surf. Sci. 30 (1972) 632.

[12] J.R. Adams and N.M. Bashara, Surf. Sci. 49 (1975) 441.

[13] K. Watanabe, M. Miyao, I. Takemoto and N. Hashimoto, Appl. Phys. Lett. 34 (1979) 518.

[14] A. Kučirkova, Rad. Eff. 28 (1976) 129.

[15] K. Nakamura, T. Gotoh and M. Kamoshida, J. Appl. Phys. 50 (1979) 3985.

[16] K. Watanabe, T. Motooka, N. Hashimoto and T. Tokuyama, Appl. Phys. Lett. 36 (1980) 451.

[17] J.W.D. Martens, W.F. van der Bogert and A. van Silfhout, Surf. Sci. 10 (1981) 275.

[18] T. Motooka and K. Watanabe, J. Appl. Phys. 51 (1980) 4125.

[19] M. Delfino and R.R. Razouk, J. Appl. Phys. 52 (1981) 386.

[20] M. Delfino and R.R. Razouk, J. Electrochemical Soc. 129 (1982) 606.

[21] B.M. Arora, J.M. Castillo, M.B. Kurup and R.P. Sharma, J. Electronic Materials, 10 (1981) 845.

[22] T. Lohner, G. Mezey, E. Kótai, F. Pászti, L. Királyhidi, G. Vályi and J. Gyulai, Nucl. Instr. Meth. 182/183 (1981) 591.

[23] T. Lohner, G. Vályi, G. Mezey, E. Kótai and J. Gyulai, Rad. Eff. 54 (1981) 251.

[24] T. Lohner, G. Mezey, E. Kótai, A. Manuaba, F. Pászti, A. Dévényi and J. Gyulai, Nucl. Instr. Meth. 199 (1982) 405.

[25] K. Nakamura and M. Kamoshida, Rad. Eff. 42 (1979) 29.

[26] J.P. Cortot and Ph. Ged, Appl. Phys. Lett. 41 (1982) 93.

[27] Zh.A. Kusainov, B.N. Mukashev, K.H. Nusupov, V.V. Smirnov, Materials of the International Working Meeting on Ion Implantation in Semiconductors and Other Materials, Prague (1981) 19.

[28] J.S. Williams, Nucl. Instr. Meth. 149 (1978) 207.

[29] G. Mezey, E. Kótai, T. Lohner, T. Nagy, J. Gyulai and A. Manuaba, Nucl. Instr. Meth. 149 (1978) 235.

[30] F.K. Naehring, J. Schöneich and A. Schmidt, Proc. Int. Conf. Ion Implantation in Semiconductors, (Budapest, 1975) 614.

[31] M. Yamaguchi, T. Hirayama, Jap. J. Appl. Phys. 15 (1976) 365.

[32] F.K. Naehring and Syhre, Proc. Int. Conf. Ion Implantation in Semiconductors, (Reinhardsbrunn, 1978) ZfK-360, vol.1. p. 25.

[33] W. Möller, Th. Pfeiffer and M. Schluckebier, Nucl. Instr. Meth. 182/183 (1981) 297.

[34] F.L. McCrackin, NBS Technical Notes 479 (1969)

[35] D.A. Thompson, G. Carter, H.K. Haugen and D.V. Stefanovic, Rad. Eff. 46 (1980) 71.

[36] J.J. Grob, P. Siffert, R. Prisslinger and S. Kalbitzer, Proc. Int. Conf. on Application of Ion Beams to Materials (Warwick, 1975) 24.

[37] R. Grötzschel, R. Klabes, U. Kreissig, J. Rüdiger and A. Schmidt, Proc. Int. Conf. on Ion Beam Modification of Materials, (Budapest, 1978) 65.

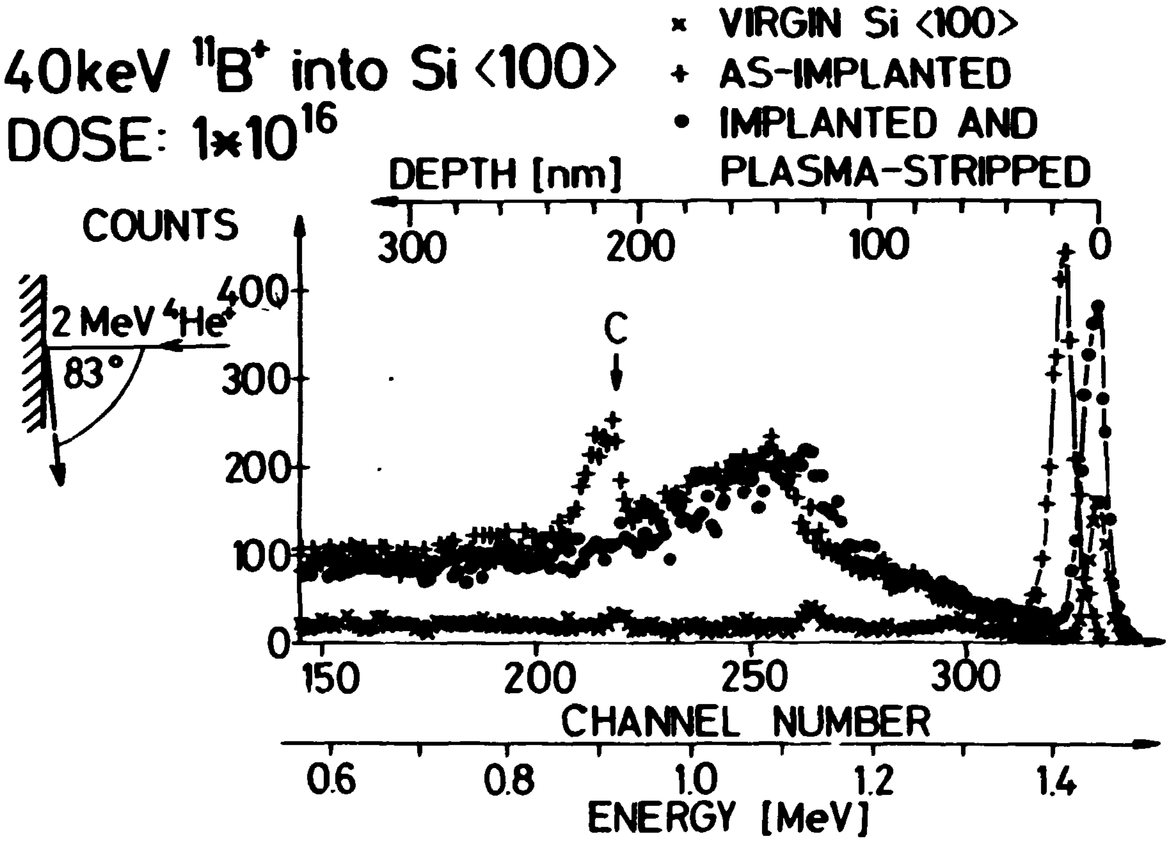

Fig. 1. Channeling spectra of $^{11}B^+$ implanted silicon along the <100> axis before and after plasma stripping

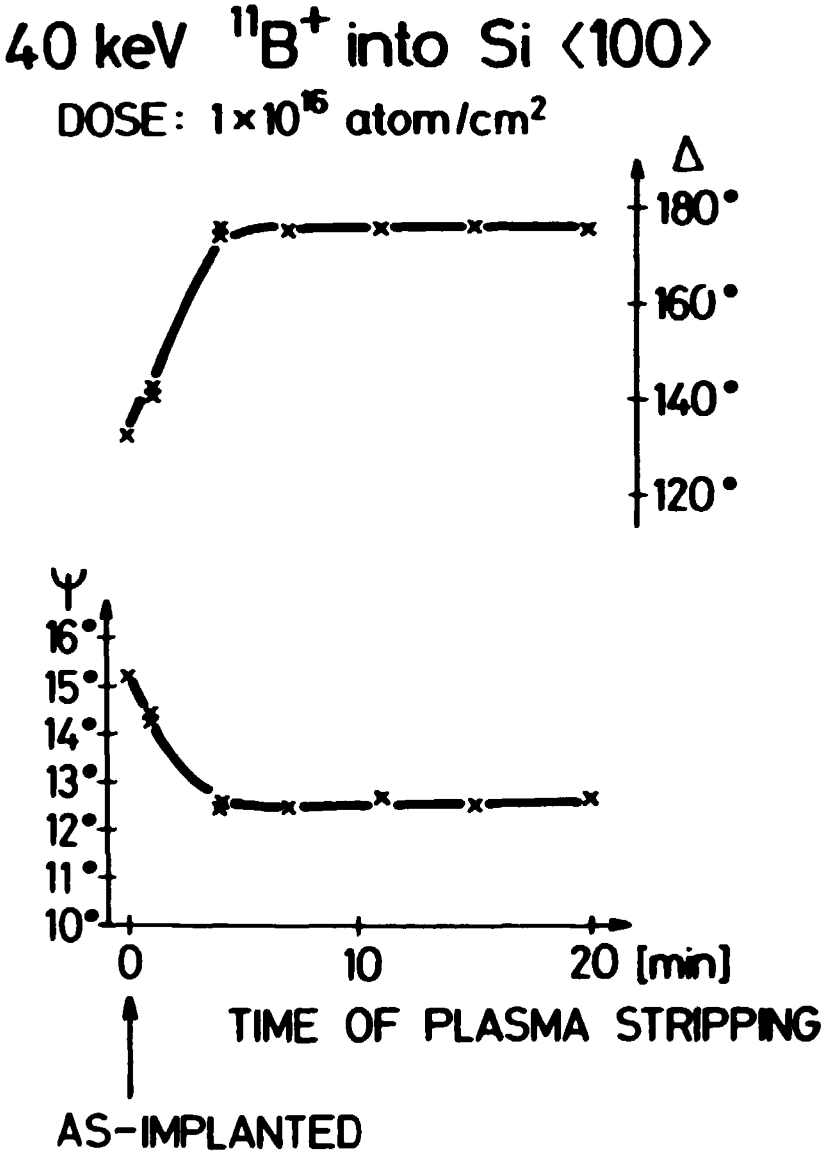

Fig. 2. Change of ellipsometric parameters as a function of time of plasma stripping

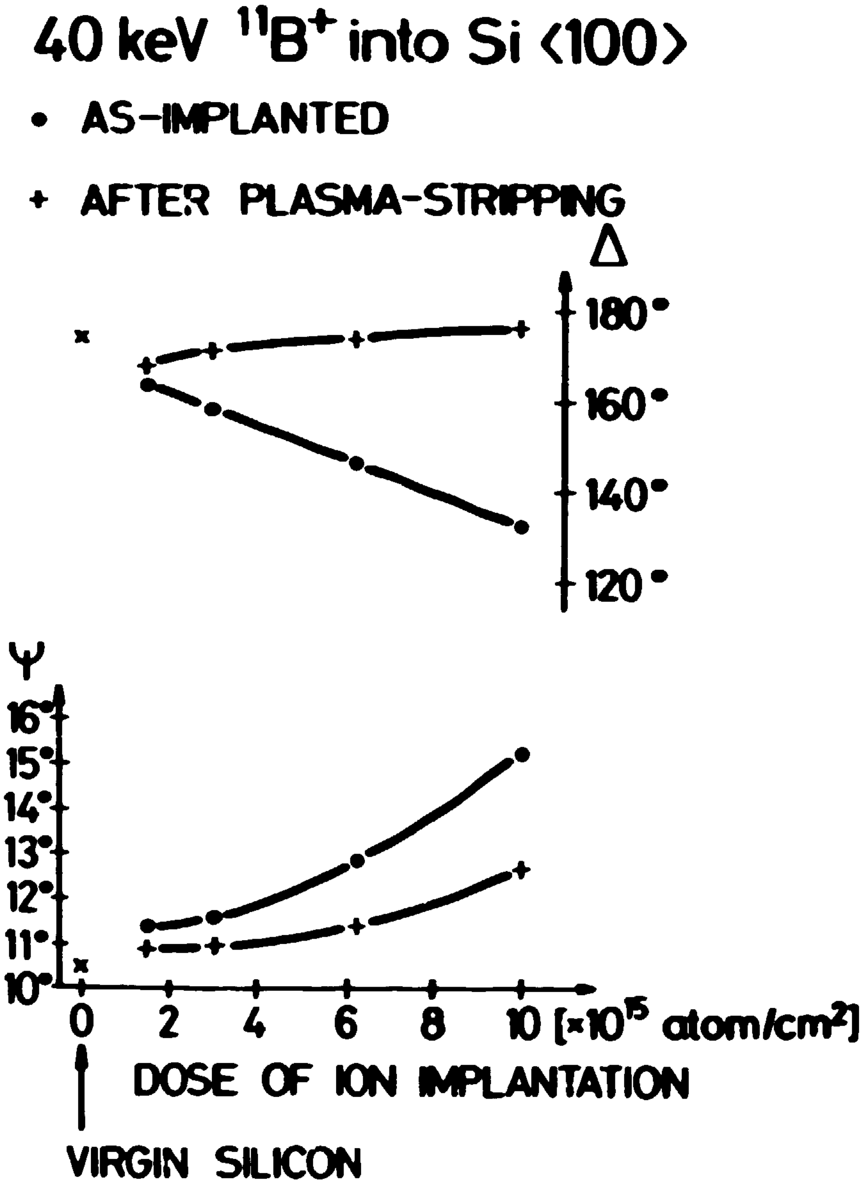

Fig. 3. Dose dependence of ellipsometric angles before and after plasma stripping

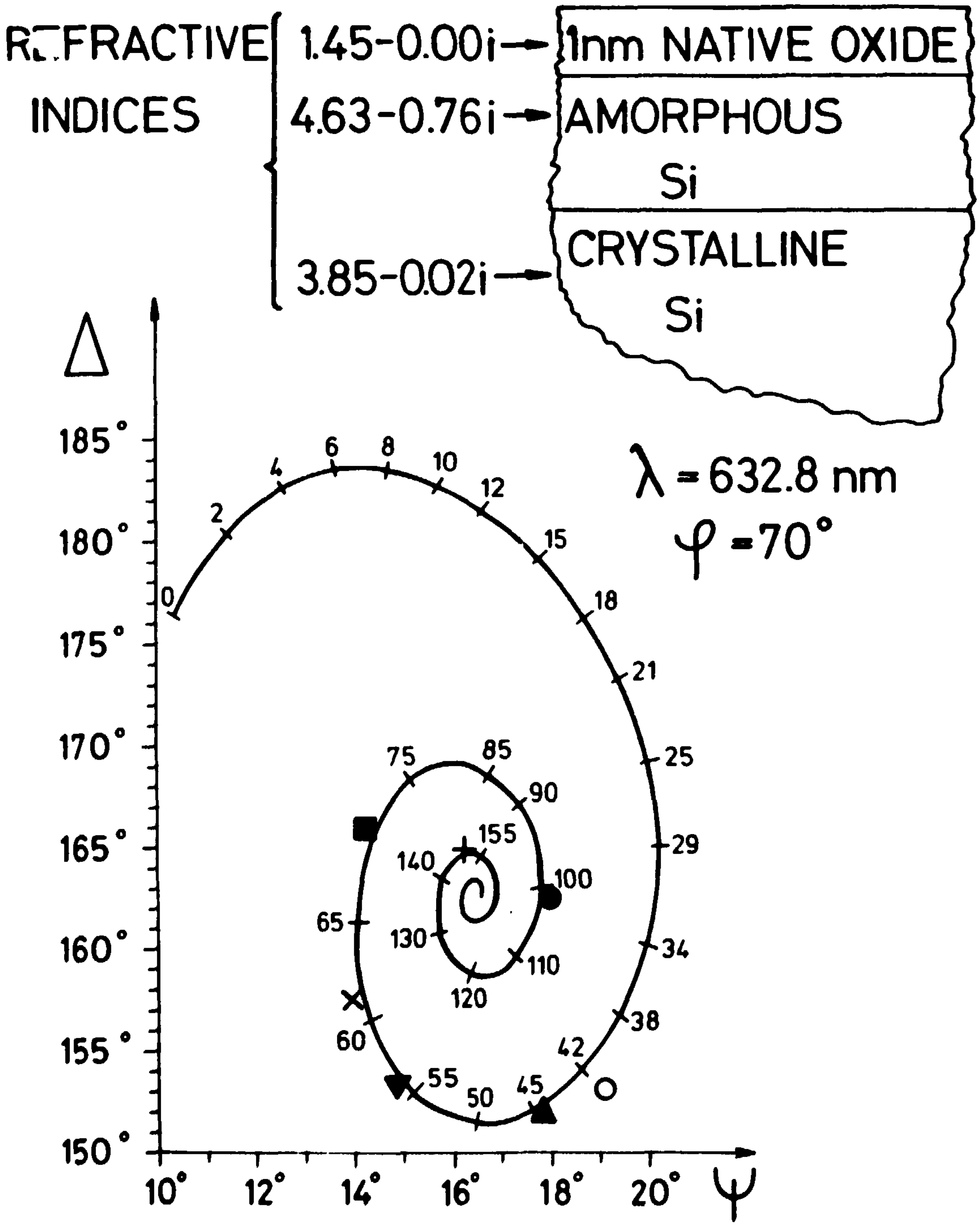

Fig. 4. *The symbols show the measured ellipsometric angles (ψ, Δ) on different ion-implanted samples (details in Table 1). The continuous curve is based on calculations using a four-phase model. The values on the curve indicate the thickness of the amorphous silicon layer in nm units.*

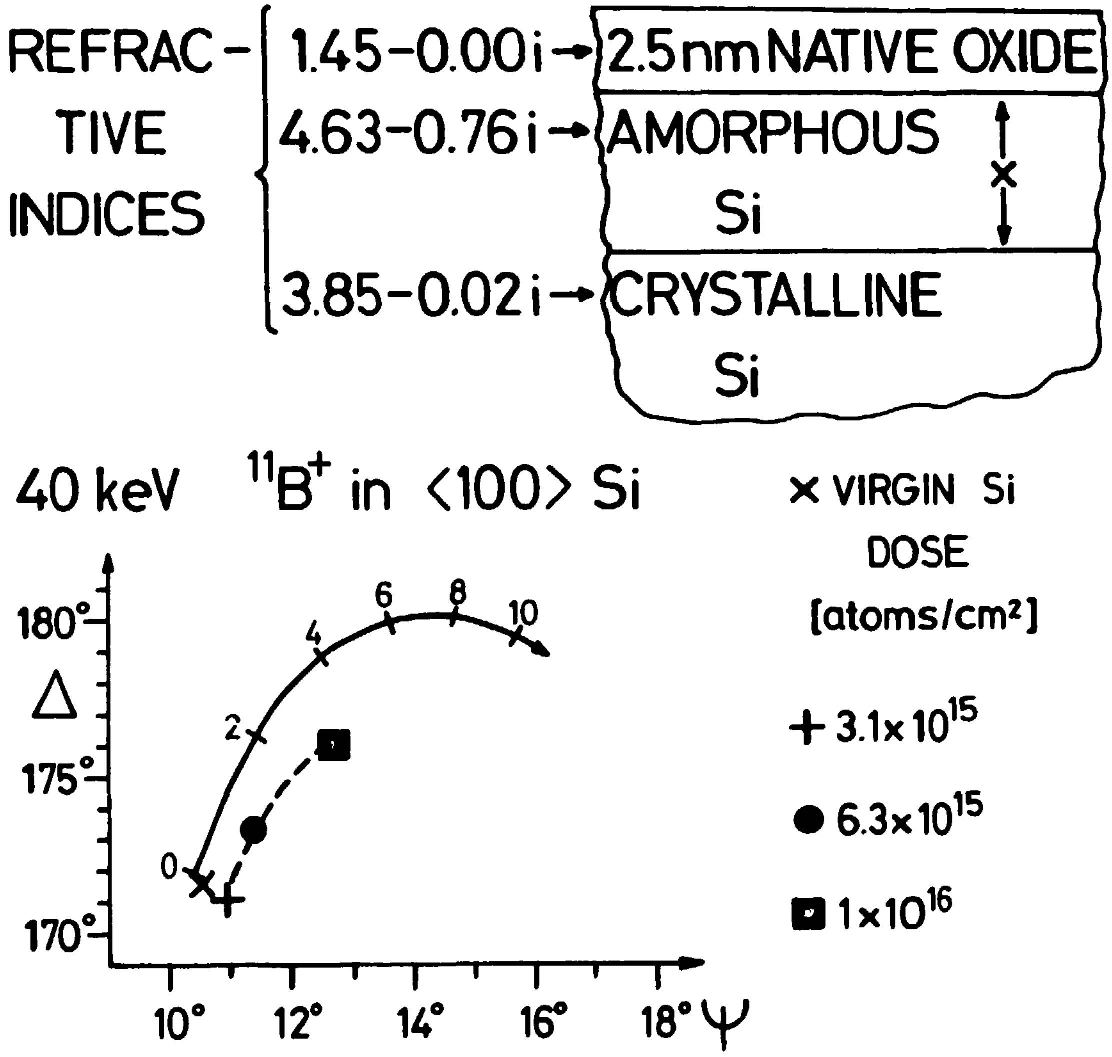

Fig. 5. The symbols show the ellipsometric angles (ψ, Δ) measured on silicon samples implanted with different doses of boron. The continuous curve is based on calculations using a four-phase model. The values on the curve indicate the thickness of amorphous silicon layer in nm units. The broken line is for guidance.

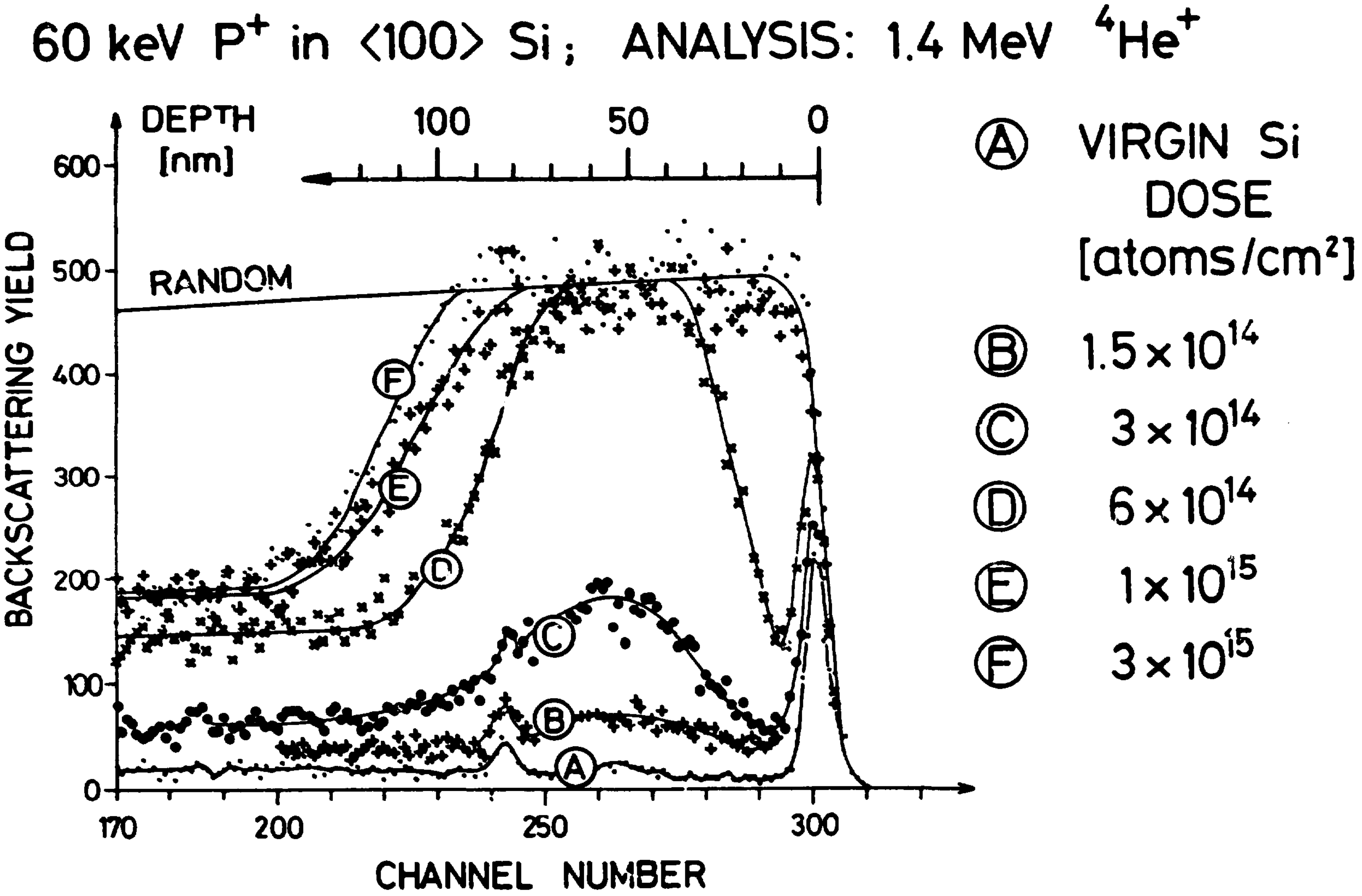

Fig. 6. Channeling spectra of $^{31}P^+$ implanted silicon along the <100> axis as a function of dose

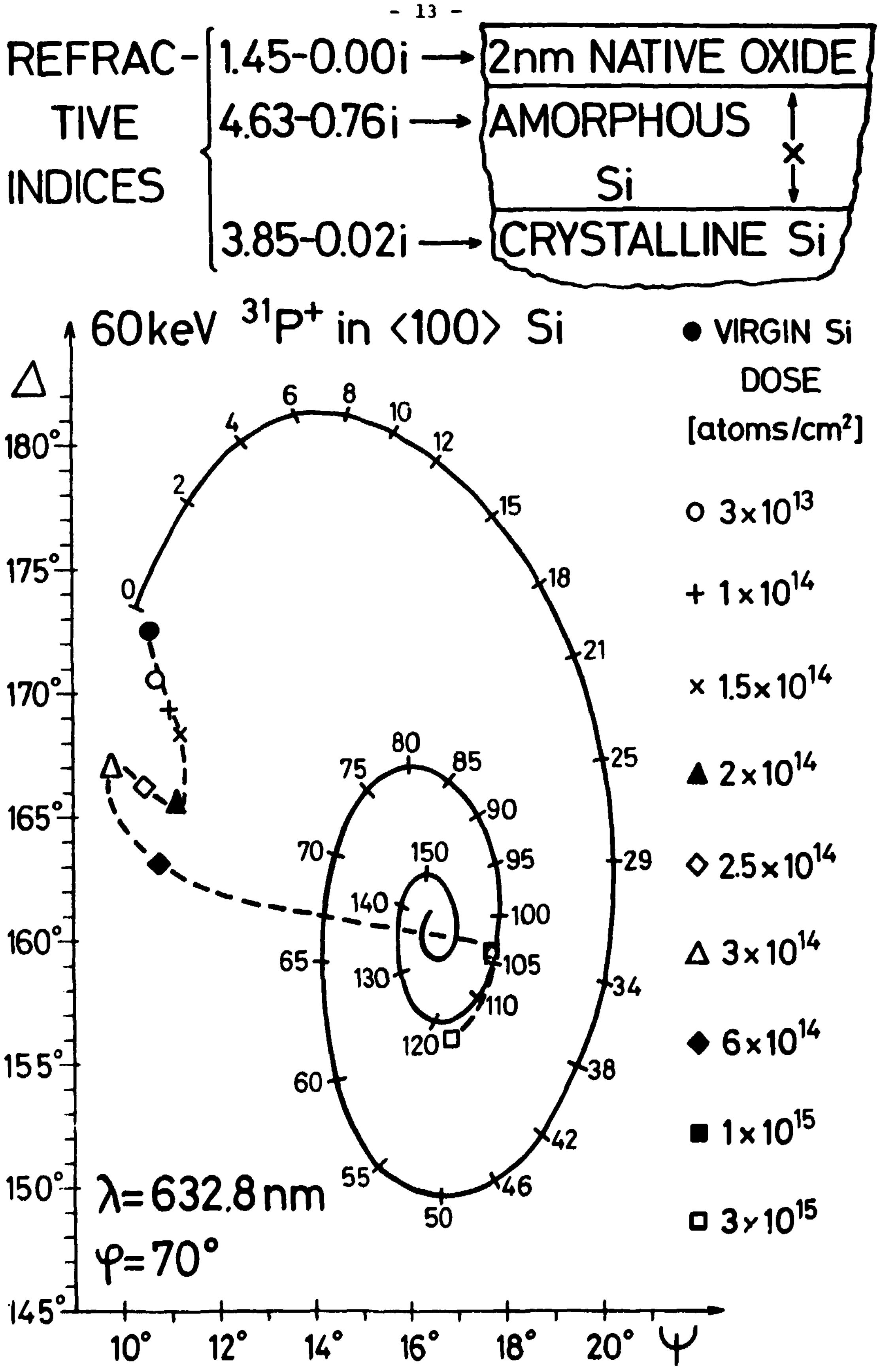

Fig. 7. The symbols show the ellipsometric angles (ψ,Δ) measured on silicon samples implanted with different doses of phosphorous. The continuous curve is based on calculations using a four-phase model. The values on the curve indicate the thickness of the amorphous silicon layer in nm units. The broken line is for guidance.

Table 1

Summary of implantation conditions. The thickness of the amorphous silicon layer was measured by channeling

Symbol	Ion	Energy [keV]	Dose atoms/cm^2	Thickness [nm]
○	$^{75}\mathrm{As}^+$	30	3.85×10^{14}	42
▲	$^{75}\mathrm{As}^+$	30	1×10^{15}	
▼	$^{40}\mathrm{Ar}^+$	30	1×10^{15}	
x	$^{209}\mathrm{Bi}^+$	80	6×10^{14}	58
■	$^{72}\mathrm{Ge}^+$	40	6.2×10^{15}	
●	$^{31}\mathrm{P}^+$	50	3.1×10^{15}	96
+	$^{28}\mathrm{Si}^+$	80 40	1×10^{16} 2×10^{15}	150

Kiadja a Központi Fizikai Kutató Intézet
Felelős kiadó: Krén Emil
Szakmai lektor: Pető Gábor
Nyelvi lektor: Harvey Shenker
Gépelte: Végvári Istvánné
Példányszám: 430 Törzsszám: 82-667
Készült a KFKI sokszorosító üzemében
Felelős vezető: Nagy Károly
Budapest, 1982. december hó