FROM ION BEAM TECHNIQUES TO NANOSTRUCTURES

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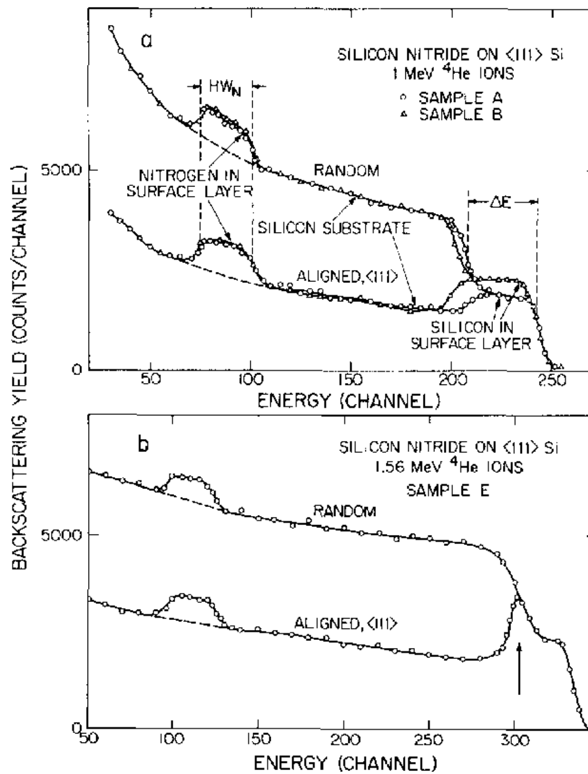
At the dawn of integrating transistors on a single chip

- – as Gordon Moore predicted and to fortune of academics – there was an open chance to apply ideas from solid state physics and chemistry.
- At next development stage, atomic scale precision of preparation techniques became critical – more engineering, less academics.
- Today, again physics is coming, but at level of quantum physics, atomic magnetism.

My encounter with ion beam techniques

- Being ’best time and best place’ occurred at Caltech as post-doc in the group of Prof. J.W. Mayer from 1969 on, for more than a decade.
- My first contribution was finding out how depth-dependent chemical composition can be extracted from Rutherford Backscattering and Channeling spectra (RBS+C).

This earned my acceptance in Mayer's group



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Because of the role of α (α makes a compression of energy scale ($E_2 = \alpha E_1$, i.e. an incoming energy interval ΔE_1 will be compressed to $\alpha \Delta E_1$, filling up α times less channels), the halfwidth ratio has to fulfill the following relation:

$$\frac{HW_{Si}}{HW_O} = \frac{\alpha_{Si} \frac{dE}{dx}\Big|_{E_1} + \frac{1}{\cos\Theta} \frac{dE}{dx}\Big|_{\alpha_{Si} E_1}}{\alpha_{ox} \frac{dE}{dx}\Big|_{E_1} + \frac{1}{\cos\Theta} \frac{dE}{dx}\Big|_{\alpha_{ox} E_1}} = 1.24$$

$\alpha_{Si} = 0.57$, $\alpha_{ox} = 0.37$, $\frac{dE}{dx}\Big|_{E_1} = 31\ eV/Å$, $E_1 = 1\ MeV$

$\frac{dE}{dx}\Big|_{\alpha_{Si} E_1} = 30.7\ eV/Å$, $\frac{dE}{dx}\Big|_{\alpha_{ox} E_1} = 27.4\ eV/Å$, $1/\cos\Theta = 1.03$

stopping powers 30.7 & 27.4 seem reasonable

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ANALYSIS OF SILICON NITRIDE LAYERS ON SILICON BY BACKSCATTERING AND CHANNELING EFFECT MEASUREMENTS*

J. Gyulai,† O. Meyer,‡ and J. W. Mayer
California Institute of Technology, Pasadena, California 91109

and

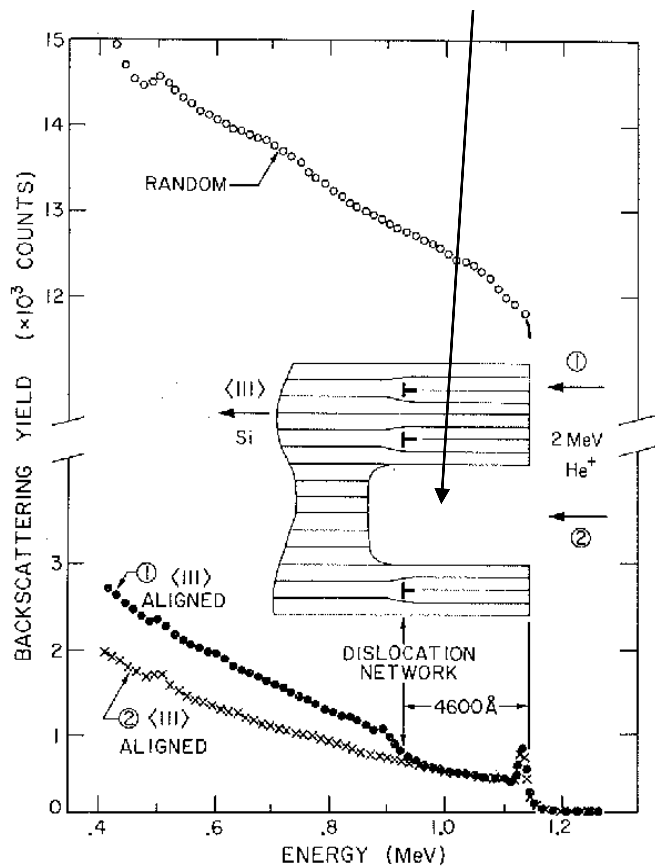
V. Rodriguez
Fairchild Semiconductor, Palo Alto, California 94304

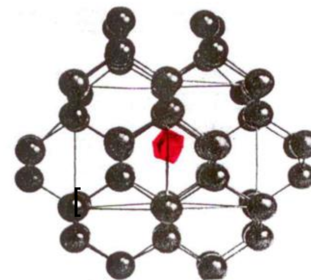
(Received 15 December 1969; in final form 26 January 1970)

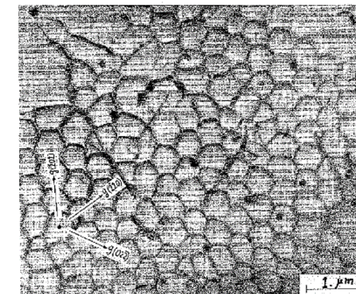
Why ”best place”?

- Co-author, Val Rodriguez, of Fairchild Development, an earlier Caltech PhD, came to visit us in fall 1969, and I got the task to explain him what we can measure and think on RBS and future of ion implantation, a too early patent of W. Shockley.
- It was just one year after Intel left the ’mother company’ and Fairchild was not yet aware of loosing all positions to Intel in the field of semiconductors,
- so it was Val who supported my work with up-to-date problems of industry and ’world’s first’ samples (11 papers in one year!)
- Intel, in its start-up phase, has not valued usefulness of implantation at all (personal discussions, 1970); this slowly changed from 1975, when R.D. Pashley, our fresh Caltech PhD, later inventor of flash memory, got a job at Intel; today
- over 20 implantation steps in production of a processor

We were adding tricks to RBS: based on that dechanneling being very sensitive to defects, e.g., with etching – area of a dislocation network was deduced







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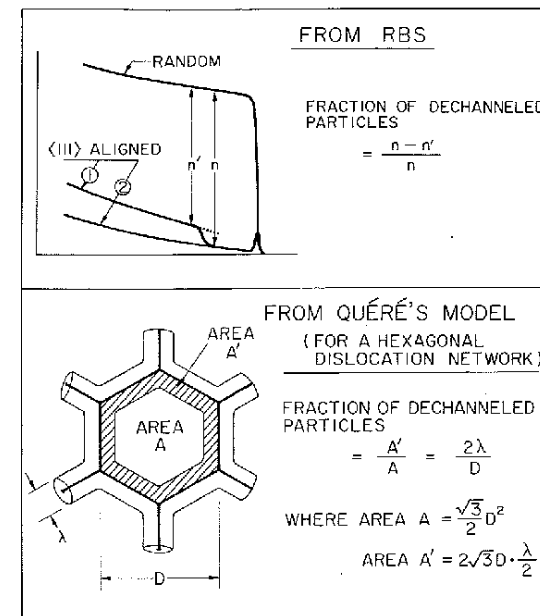
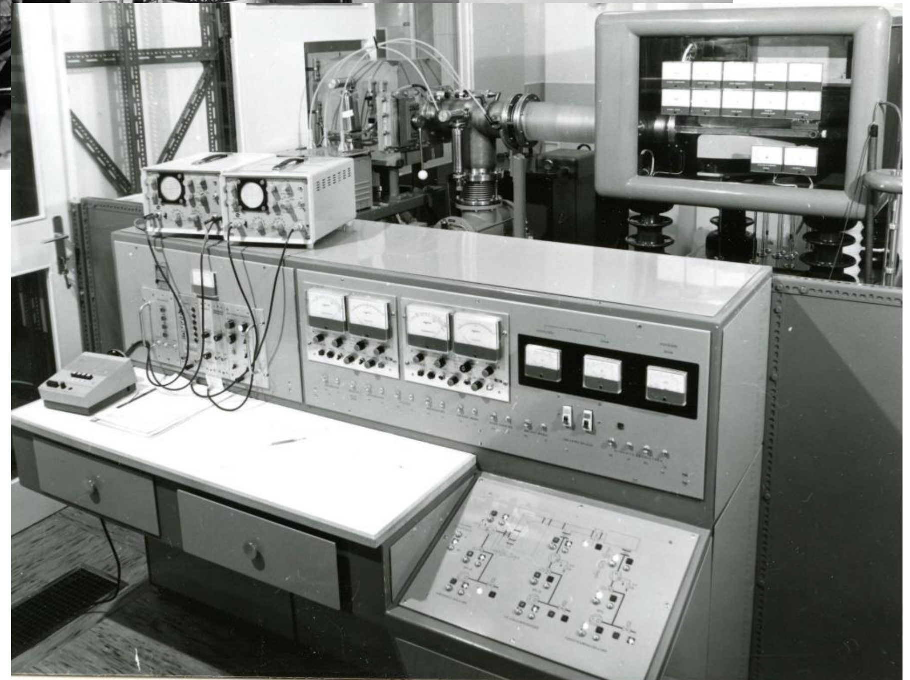


W.F. Tseng, J. Gyulai, S.S. Lau, J. Roth, T. Koji, J.W. Mayer: Nucl. Instr. Meth. 149, 615 (1978)

My life after joining my family

- Back to Hungary in 1970, organization of a new facility on ion implantation in semi-conductors and on nuclear analytical techniques was the task of a new group at the ‘that-time’ **C**entral **R**es. **I**nst. of **P**hys., KFKI, where I’ve been invited to join.
- From 1974 on, an NSF-supported Caltech-KFKI exchange program, maybe the first with an Eastern bloc country, involving Mayer’s and Gyulai’s group made the Budapest group accepted in international community

Our first two equipment for implantation



The Kurchatov mass separator ILU-2 at KFKI (above);

High current ion source was designed by M. von Ardenne (as a 'POW' in the Soviet Union)

Our home made 150 kV implanter, SAFI, E. Pasztor's group (right)

Main contributions of the NSF-supported “Mayer-Gyulai” group

- Proving that as substrate (100)-oriented silicon is preferential not only for oxide quality, but also for better reordering of implantation defects – contribution to paradigm change of silicon crystal industry (H. Müller, W.K. Chu, J. Gyulai, J.W. Mayer, T.W. Sigmon, T.R.Cass: APL 26, 292 (1975))

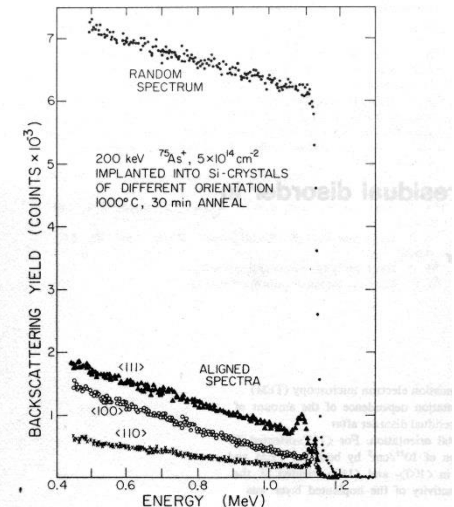
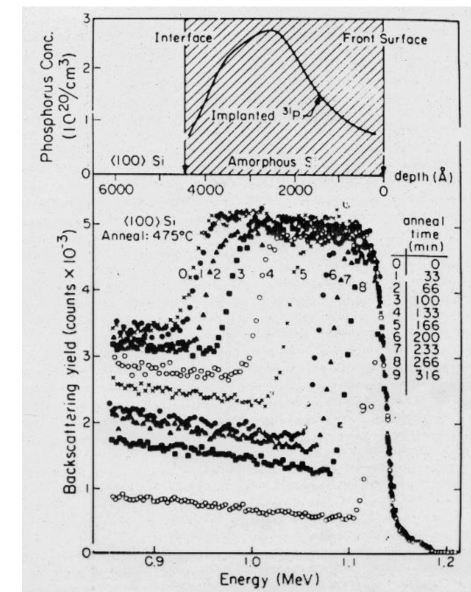


FIG. 1. 2-MeV He^+ random and aligned backscattering spectra for 200-keV 5×10^{14} As/cm^2 implanted into Si crystals of ⟨111⟩, ⟨100⟩, and ⟨110⟩ orientations and annealed at 1000°C for 30 min in dry N_2. The channeling axis coincides with the surface normal.

- The “Pre-amorphization” technique, curing most negative effects of implantation, proved to be crucial for implantation to become industrial practice;1) amorphization with Si/Ge ions, 2) implantation of dopant, 3) proper anneal; main contributor our L. Csepregi, e.g., JAP 48, 4234, 1978



The NSF-CRIP (KFKI) program resulting in 32 joint papers in first years. Right: Westerners involved

FINAL TECHNICAL REPORT

Submitted to

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Division of International Programs

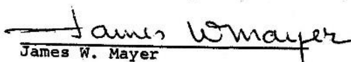
on

ION IMPLANTATION IN SEMICONDUCTORS

(A Joint Research Project Between the California Institute of Technology, Pasadena, California and the Central Research Institute for Physics, Budapest, Hungary)

June 1, 1978 to November 30, 1980

Principal Investigators (Caltech)


James W. Mayer

Marc-A. Nicolet

Principal Investigator (Budapest)

Jozsef Gyulai

1 September 1980

III. Data on Scientific Collaborators.

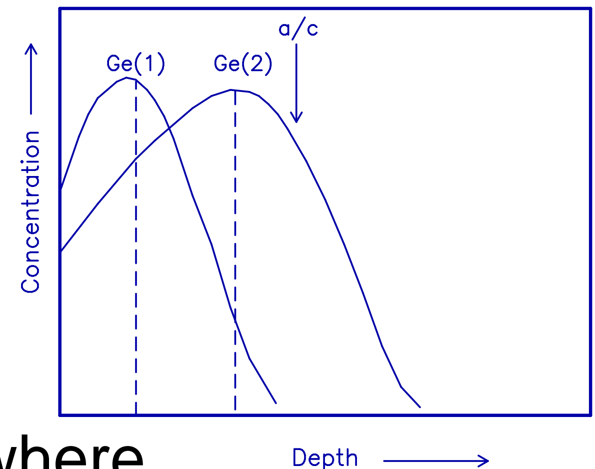
The following were engaged in research under Grant No. INT78-08779 at the California Institute of Technology:

Co-Investigator	Status	Present Address
Wei-Kan Chu	Research Fellow	IBM, East Fishkill Facility, Route 52 Hopewell Junction, N.Y.
Charles A. Evans*	Research Fellow	CHARLES EVANS & ASSOCIA 1670 S. Amphlett Blvd. San Mateo, California
Gaetano Foti	Visiting Research Fellow	Istituto di Fisica 57, Corso Italia *-95129 Catania, Italy
Edward F. Kennedy	Visiting Research Fellow	Physics Department College of the Holy Cro Worcester, Massachusett
Tetsu Koji	Visiting Research Fellow	359 Doi, Tosa-cho,Tosa-Kochi-ken,781-34,Japan
Silvanus S. Lau	Senior Research Fellow	Caltech
Samuel E. Matteson*	Research Fellow	Texas Instruments Dallas, Texas
James W. Mayer*	Professor	Caltech
Helmut Müller	Visiting Rsearch Fellow	Siemens Aktiengesellschaft FL FKS 111 Hofmannstr. 51 8000 München 70, Germany
Marc-A. Nicolet*	Professor	Caltech
Peter Pronko	Visiting Research Fellow	Argonne National Lab. Argonne, Illinois
Joachim Roth	Visiting Research Fellow	Max-Planck-Institut für Plasmaphysik, München, Germany
Thomas W. Sigmon	Visiting Research Fellow	Stanford Electronic Lab. Stanford University Stanford, California
Wen F. Tseng	Research Fellow	Naval Research Lab. Washington, D. C.
Marc Wittmer	Visiting Research Fellow	BBC Brown Boveri & Co.,Ltd Research Center, KLR Baden, Switzerland

*Also, Visiting Scientist at CRIP.

My years, 1988-2000, with Prof. H. Ryssel, at and with FhG-Inst. für Integrierte Schaltungen-B, Erlangen

- Being ”Zweitgutachter” of seven students there
- One example: To success of implantation “Defect engineering” developed as science on verge of solid state physics and engineering
- Because of forward peaking character of implantation, type of damage closer to surface is vacancy rich, deeper interstitial rich



- Using multiple energy non-doping implantation, a layer can be produced, where relations are more balanced and conditions for defect reordering are favourable (JG at FhG IIS-B: C. Dehm, J. Gyulai, and H. Ryssel, Appl. Phys. Lett. 60 (1992) 1214)

The KFKI, now the MFA semiconductor group

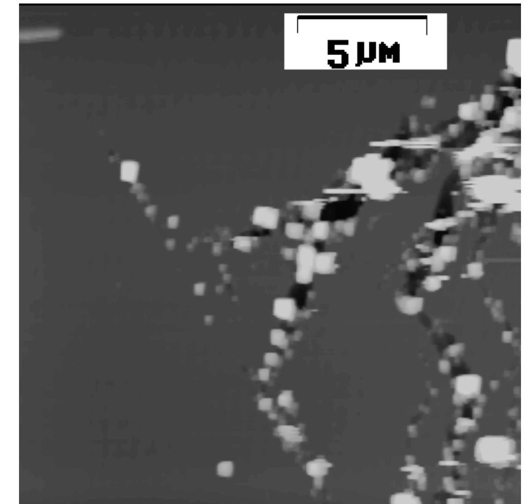
- Already from the late eighties we've switched to sensorics as a field, where our full, though limited capability semiconductor line allowed us to reach noticeable and applicable results.
- Today, especially, in the field of Micro- and Electromechanical Systems, MEMS, e.g., lab-on-chip type novelties (I. Barsony, P. Fürjes, Cs. Dücsö, M. Serényi, et al.).
- A strong electron microscopy group with long tradition is partner in numerous EU projects and also supporter of local research (P. Barna, A. Barna, G. Radnoczi, J. Labar, B. Pecz, et al.).

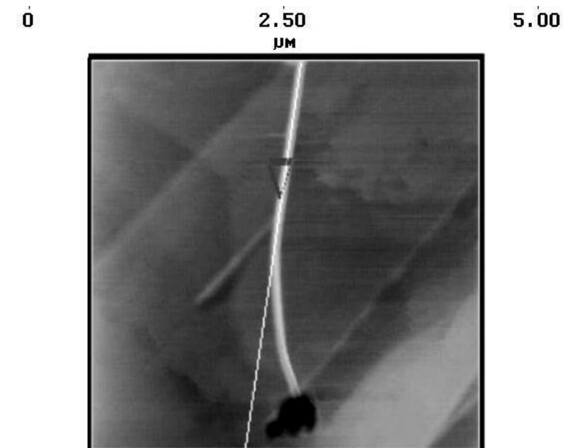
The Budapest RBS – IBA Group

- Working on its own, numerous methods, SW solutions were developed by the group improving capabilities of Ion Beam Analysis, IBA – RBS simulation, PIXE simulation, influence of multiple scattering, etc. (E. Kotai, †F. Pászti, G. Vizkelethy, E. Szilágyi, G. Battistig, et al.), (longest supported) cooperation with CNRS Groupe des Phys. des Solides, Paris VII, G. Amsel, I. Vickridge, et al. (JG, E. Szilágyi, G. Vizkelethy, G.Battistig, †É. Vázsonyi, et al.)
- Cooperation with Sevilla, Lisbon, with M. Takai, Osaka University (T. Lohner, †F. Pászti, JG), also contributed to gain reputation in IBA community.

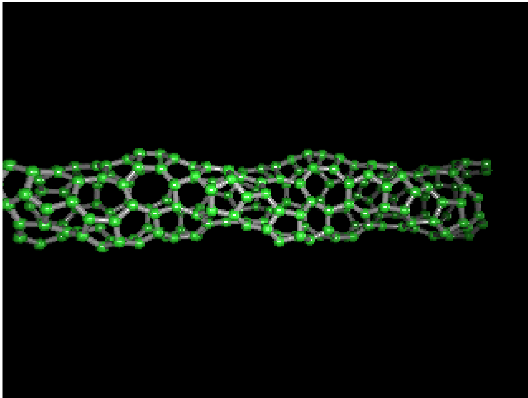
Toward nanoscience in Budapest

- Scanning probe measurement of last jumps at swift ion damage (L.P. Biró, J. Gyulai, and K. Havancsák, A.Yu. Didyk, S.Bogen, and L.Frey: Use of atomic-force microscopy and of a parallel irradiation geometry for in-depth characterization of damage produced by swift Kr ions in silicon. Phys. Rev.B, 54(1996)11853-11856),
- Discovery of carbon nanotube (CNT) condensation from plasma of swift (>200 MeV) ion impact crater (with L.P. Biró and K. Havancsak, PR B, 52 (1995) 2047)
- With heavy ions (Xe) single wall (SW), light ion (Ne) multiwall MWCNT forms – showing influence of plasma density and of cooling rate



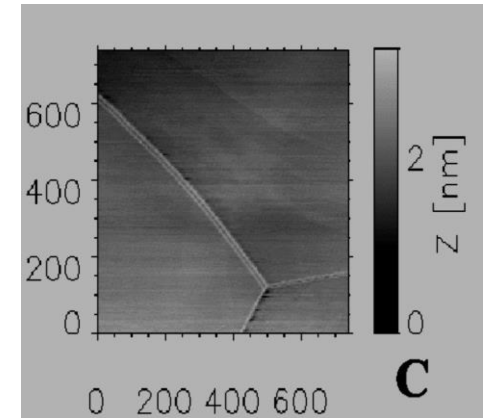


Forms of nanostructures



Forms of nanostructures by incorporating 5- and 7-atom rings

P. Nagy, R. Ehlich, L.P. Biró, and J. Gyulai: Y-branching of single walled nanotubes, Appl. Phys. A 70(2000)481-483



The Biró-Tapasztó group today focuses on 2D-materials (graphene, Mo-disulphide, bionanostructures, structuring, lithography), etc., visit www.nanotechnology.hu,

E.g., L.Tapasztó, G. Dobrik, P. Lambin, L.P. Biró: Nature Nanotechnology **3**, 397(2008)

This conference: Burgen Scholar talk of P. Vancso

Let me truly appreciate those colleagues, who helped and proposed me to become member of this prestigious Academy – the honour is shared among members of groups to whom my long career was bound.