PROFESSOR HERZL AHARONI

CURRICULUM VITAE

THIS DOCUMENT SUMMERIZES OVER FIFTY YEARS (since 1964) OF ACTIVITIES IN ACADEMIC AND RESEARCH INSTITUIONS

1. PERSONAL DETAILS

Place & Date of Birth: Haifa, Israel, 18/12/1937
Marital Status: Married, 4 (adult)children .

Work Address: Ben-Gurion University (BGU) of the Negev
Department of Electrical and Computer Engineering
P.O.B. 653, Beer-Sheva 84105, Israel
Departmental Office Fax. +972-8-6472949
Departmental Office Tel. +972-8-6461518
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Home Tel. (evenings) +972-8-6469030

2. EDUCATION B.Sc. (Nov. 1964); M.Sc. (May 1967);
Dipl. Ing. (March 1970); D.Sc. (Nov. 1972)
Faculty of Electrical Engineering,
Technion, Israel Institute of Technology (IIT), Haifa, Israel.

3. PROFESSIONAL REGISTRATION-Chartered Engineer (C.Eng.), U.K. 2003.

4. HONORS

Fellow of the European Physical Society(EPS),2018.

Citation: ***"For his ground breaking contributions and accomplishments in the invention, research, development, and realization of wide range of practical, cost-effective, efficient, single crystal Silicon Light Emitting Devices and by pioneering a systematic transformation of physics into technology".***

Fellow of The Optical Society of America(OSA)2016.

Citation: ***"for pioneering achievements in the invention and realization of cost-effective efficient two and multi-terminal single crystal Silicon Light Emitting Devises through original designs, research and development, using standard IC technology for all-Silicon monolithically integrated optoelectronic systems".***

Fellow of The International Society for Optical Engineering (SPIE), 2011.

Citation: ***"For achievements in integrated silicon LEDs, and ITO properties research for ITO/InP solar cells"***

Fellow of the American Physical Society (APS), 2007.

Citation: ***"Pioneering contributions to the invention, research, and development of two-and multi- terminal Single Crystal Silicon Light Emitting Devices (SiLEDs) for all-silicon integrated optoelectronic systems, combining semiconductor physics and standard IC technology."***

Fellow of the Institute of Physics (IOP), 2005.

HONORS(Cont.)

Fellow of the Institution of Engineering and Technology (IET) 2003, (Formerly IEE).

Fellow of the South African Institute of Electrical Engineers(SAIEE),2016

Certificate of Recognition and Appreciation-by the IEEE Electron Device Society.
Citation:
"**In Recognition and Appreciation of Valued Services and Contributions as EDS Distinguished Lecturer 2003 to 2015".**
Awarded by Samar Saha, President, Electron Devices Society, December 2017.

Certificate of Recognition and Appreciation – by the IEEE Electron Device Society. **Citation:**
"In Recognition and Appreciation of valued contributions as EDS Distinguished Lecturer since 2003".
Awarded by Cor Claeys, President of the Electron Device Society, December 2009, Baltimore, MD, USA.

Appear in the IEEE "2007 Golden List of Reviewers"
IEEE Transactions on Electron Devices, Vol.54, No.12, December 2007, P. 3117.

Appear in the IEEE "2014 Golden List of Reviewers"
IEEE Transactions on Electron Devices, Vol.61, No.12, Dec.2014. PP.3920-3948.

Appear in the IEEE "2015 Golden List of Reviewers"
IEEE Transactions on Electron Devices, Vol.62, No.12, Dec.2015, PP.3906-3937.

The 2010 "iNEER Achievement Award" - Presented by the international advisory board of the International Network for Engineering Education &Research (iNEER). July 21,2010.
Citation:
For his Contribution in New Knowledge CreationThrough Innovative International Educational and Scientific Collaboration with Academic and Research Institutions.

Supervised a research and co-authored a resulting graduate student paper, which received the "Young Researcher Award" of the International Conference on Solid State Devices and Materials (SSDM 2000, Tokyo, Japan- see list of publications). Presented at the SSDM 2001, September 26, 2001.

The Ben-Gurion University Prize, 1998, for contribution in applied electronics research on the subject of "chemical vapour deposition of silicon-germanium heteroepitaxial structures", donated by the Polish Jewish Ex-Servicemen's Association of London.

Distinguished Research Professor - in the Materials Laboratory, Faculty of Engineering, Rand Afrikaans University, Johannesburg, South Africa, 1990

U.S.A National Research Council (NRC) - National Aeronautics and Space Administration (NASA) Research Associateship Award, 1979–1980, for performing a research at the Jet Propulsion Laboratory (JPL), Pasadena, California, U.S.A.

"Career-long Excellence in Teaching Award"

Citation: ***In honor of many years of excellence pertaining to his activities to advance teaching at the university and his efforts to enhance the prominence of its academic excellence to the highest degree, as well as his nurturing of future generations of those who seek knowledge and science***.

Awarded by the President and Rector of Ben-Gurion University, Beer-Sheva, Israel, Nov.6, 2017.

“Outstanding Teaching award”

Citation:

"In honor of his work in pursuit of the advancement of teaching, and contribution to the enhancement of the reputation of the university as a center of academic excellence of the highest degree, for the benefit of future generations earnestly seeking knowledge and science"

Awarded by the President and Rector of Ben-Gurion University, Beer-Sheva, Israel, June 22, 2006.

A Letter of Commendation for Teaching Excellence for the 2006 Academic year, by the Dean of the Faculty of Engineering Sciences, Ben-Gurion University of the Negev, Beer-Sheva, Israel.

"Excellence-in- Teaching Award".
Ben- Gurion University, Beer-Sheva, Israel.
Awarded by the Dean of the Faculty of Engineering, November 9, 2006

“Outstanding Teaching award” - Awarded by the President and Rector of Ben-Gurion University, Beer-Sheva, Israel, June19, 2005.
Citation - same as in 2006

A Letter of Commendation for Teaching Excelence for the 2005 Academic year, by the Dean of the Faculty of Engineering Sciences, Ben-Gurion University of the Negev, Beer-Sheva, Israel.

"Excellence-in- Teaching Award".
Ben- Gurion University, Beer-Sheva, Israel.
Awarded by the Dean of the Faculty of Engineering, December1, 2005.

A Letter of Commendation for Teaching Excelence for the 2004 Academic year. By the Dean of the Faculty of Engineering Sciences, Ben-Gurion University of the Negev, Beer-Sheva, Israel.

"Excellence-in- Teaching Award".
Ben- Gurion University, Beer-Sheva, Israel.
Awarded by the Dean of the Faculty of Engineering, 2004.

Teaching Excellence Award.
Awarded by the Rector of Ben-Gurion University, as a Best Teacher in the Faculty of Technological (engineering) Sciences. Beer-Sheva, Israel 1988.

"Esteemed Teacher" Certificate.

Citation: ***This certificate is awarded in recognition of your election as an esteemed lecturer. We trust that your contribution to students and to the overall quality of education will serve as an example to others.***

Awarded by the Students' Association of Ben-Gurion University of the Negev, Beer- Sheva, Israel,1988

Teaching Excellence Award.

Awarded by the Rector of Ben-Gurion University, as a Best Teacher in the Faculty of Technological (engineering) Sciences. Beer-Sheva, Israel 1987.

Graduate School scholarships throughout graduate studies (M.Sc. and D.Sc.),1965-1972.

Invited Paper (co-author)- Proceedings of the IEEE 12th International Conference on Mixed Design of Integrated Circuits & Systems, MIXDES 2005, 23-25 June, 2005, Krakow, Poland (See list of publications).

Invited Paper (co- author) - Proceedings of the 12th IEEE International Symposium on Electron Devices for Microwave and Optoelectronic Applications, EDMO 2004. Kruger National Park, South Africa, November 2004 (See list of publications).

Plenary Session Paper(co-author) - Kariega 2004 Conference on Photo – Responsive Materials, 25 – 29 February 2004, Kariega Game Reserve, South Africa (See list of publications).

Invited Paper (co-author) **-** Proceedings of the International Semiconductor Conference CAS 2001, Sinaia, Romania, October 2001(See list of publications).

Invited Paper (co-author) - Proceedings of the International Society for Optical Engineering (SPIE) and Photonics West "Optoelectronics 2000" symposium, January 2000, San Jose, California, USA (See list of publications).

IEEE EDS Distinguished Lecturer Plenary Session Invited Talk- Proceedings of the MSMW'2010 International Kharkov Symposium, June 2010, Kharkov, Ukraine. (See list of publications).

5. BIOGRAPHICAL SUMMRIES

Biographical summaries are published in the following books:

Who's Who in Science and Engineering.
Who's Who in the World.
Directory of International Biography (IBC).
2000 Scientists of the 21st Century (IBC).
Outstanding Scientists of the 21st Century (IBC).
The Cambridge Blue Book (IBC).

6. EMPLOYMENT HISTORY AT BEN-GURION UNIVERSITY

Post retirement position:

Following my retirement (mandatory) from Ben-Gurion University on February 1, 2007, after over thirty four years, I maintain my office at the university and continue my teaching and research activities at the department of Electrical and Computer Engineering.

Contact Details: Same as cited in page 1.

Present Rank: **Professor Emeritus** (since February 1, 2007)

Regular Employment period at Ben-Gurion University:

March1, 1973 to January 31, 2007- Full time permanent member of the Department
Of Electrical and Computer Engineering, Ben-Gurion University (BGU) of the Negev, Beer-Sheva, Israel. This period includes activities in other institutions (Universities, research laboratories) during my sabbaticals, leaves, and summer positions, as listed below (paragraph 7).

Academic Ranks:

Full Professor- October 1, 1993.
Associate Professor- October 1, 1984.
Senior Lecturer- April 1, 1977.
Lecturer- April 1, 1973.

During my work at the University, I have served in the following capacities:

Teaching activities: In charge of instruction and curriculum development of electronic devices, electronic circuits, semiconductor technology and microelectronics.

Teaching the following courses -

Compulsory courses: Electronic devices - second year students.
Linear Electronic Circuits - third year students.

Elective courses: Semiconductor Technology (4th year & graduate students)
Integrated circuit fabrications (4th year& graduate students)
Special semiconductor devices (graduate students).

Laboratories: Academic head of Electronic Devices and Microelectronics Laboratory.
Academic head of Electronic Circuits Laboratory.

Other activities: Academic head for senior (4th) Year Projects.
Faculty Student course Counsellor (for 1st, 2nd, 3rd and 4th year students).
Chairman/Member of the Departmental Committee on Curriculum and Academic Affairs.
Member of the Departmental Committee for Appointments and Promotions.

Member of Council of the Faculty of Technological Sciences.
Member of University Senate (1984 – 2004).

Community Service: Member of Israeli Government Interdepartmental Committee for Microelectronics Development in Israel (appointed by Minister of Science and Technology Professor Yuval Ne'eman August 1991).
Reviewer for the NRF (National Research Foundation) of South Africa, for the scientific evaluation of university faculty members (since 1984).
Chairmen of a committee appointed by the Governmental Council for Higher Education (J/S), for upgrading the B.Tech degree to B.Sc degree, in the Department of Electrical Engineering at the Arial Collage.

7. ACTIVITIES IN OTHER INSTITUTIONS (INCLUDING SABBATICALS, LEAVE OF ABSENCE, SUMMER VISITING POSITIONS).

March 2006-Feb.2007 — Tohoku University, Sendai, Japan.
New Industry Creation Hatchery Center (NICHe).
Fluctuation Free Facility (FFF), Ohmi Laboratory.
Growth of microcrystalline and amorphous thin silicon films, by plasma enhanced radical based low temperature deposition (300°C), as a part of low cost large area tandem solar cells Project.
(Total of 11 months)

July – October 2003
July - October 2002 — University of Pretoria, Pretoria, South Africa, Faculty of Engineering, Built Environment and Information Technology, Dept. of Electrical, Electronic and Computer Engineering, Carl and Emily Fuchs Institute of Micro-electronics (CEFIM)
Research for the fabrication of low operation voltage, (<5V) integrated silicon light emitting devices (Si-LED's), for single supply operation of IC/Si-LED integrated systems
(Total of 6 months).

Aug 1999 – Sept 2001 — Tohoku University, Sendai, Japan
Aug 1999 – March 2000, Research Institute of Electrical Communication (RIEC), Professor.
April 2000 – Sept 2001, New Industry Creation Hatchery Center (NICHe), Visiting Professor.
Research on Low-Temperature Processing of Silicon Electronic Devices and related materials.
(Total of 26 months).

July - Oct. 1998
July - Oct. 1997
February 1996 — University of Pretoria, Pretoria, South Africa, Faculty of Engineering, Dept. of Electrical and Electronic Engineering, Carl and Emily Fuchs Institute for Microelectronics (CEFIM).
Research on producing multi-terminal integrated Silicon Light Emitting Devices (Si-LED's) using Standard IC-processing without any alteration of the processing, in order to produce all-silicon optoelectronic circuits and systems, which will be viable both in performance and economically.

	PATENTS – 8 patents. (See list of publications) (Total of 9 months).
April 1994 - Jan. 1996	Tohoku University, Sendai, Japan, Department of Electronic Engineering, Faculty of Engineering. Working in Super Clean Rooms, which are predesigned and built for the research and development of future Ultra Large Scale Integration (ULSI) devices and circuits. Investigation of device performance and influence of post implantation annealing processes and temperatures on junctions produced in ultraclean environment. (Total of 22 months).
Aug. 1993 - March 1994 July - October 1992 January/February 1992 June - September 1991	University of Pretoria, Pretoria, South Africa, Faculty of Engineering, Dept. of Electrical and Electronic Engineering, Carl and Emily Fuchs Institute for Microelectronics (CEFIM). Research on producing integrated Silicon Light Emitting Diodes (Si-LED's) using Standard IC processing without any alteration of the processing, in order to produce all-silicon optoelectronic circuits and systems, which will be viable both in performance and economically. (Total of 15 months).
July - September 1990 June - September 1989	RAU Rand Afrikaans University, Johannesburg, South Africa, Materials Engineering Laboratory - Microelectronics Laboratory. In-Situ reflectivity measurements of ion implanted single crystal silicon using a computerized optical reflectivity system built into an existing ion implantation system. Determination of the changes of material properties pertinent to device fabrication during real implantation time. (Total of 5 months).
July - October 1988	McGill University, Montreal, Canada - Physics Department, Semiconductor group. Deposition of ZnSe by OM-CVD using modified Atomic Layer Epitaxy of single crystal epitaxial layers on GaAs substrates. N^+(ZnSe)/N(GaAs) junction formation and characterization. (4 months).
July - October 1987	IMEC - Interuniversitair Micro-Elektronica Centrum VZW, Leuven, Belgium. MBE deposition of GaAs epitaxial layers on Si single crystal substrates. Process development of a new procedure for Si surface treatment, mainly within the MBE system for III - V materials deposition on Si substrates. (4 months).
July 1984 - October 1986	SERI-Solar Energy Research Institute, Golden, Colorado, U.S.A... Processing of III-V photovoltaic devices (GaAs; GaAsP), fabrication of ITO/InP solar cells, ITO properties study. (Total of 26 months).

July - October 1981/82/83 — RAU-Rand Afrikaans University, Department of Electrical & Electronic Eng., Johannesburg, South Africa.
Ion implanted single crystal silicon solar cells, Amorphous silicon research, related subjects.
(Total of 10 months).

July 1979 - October 1980 — JPL- Jet Propulsion Laboratory, Pasadena, California, U.S.A. – National Astronautics and Space Administration program, Control and Energy Conversion Division - Advanced Photovoltaic Development Group.(July 15,1979-October 15, 1980).
Participation in a research program on thin - film single - crystal GaAs Solar Cells grown by OM-CVD onto interlayer of Ge grown (C.V.D.) on Si substrate(15 months).

1978 - 1979 — UCSD- University of California at San Diego, California, U.S.A.
Visiting Associate Professor at the Applied Physics and Information Science Department*.
Teaching of Semiconductor Electron Devices, Semiconductor Technology, and Basic Electrical Engineering, (circuit analysis)
(10 months).

* Later on - Dept. of Electrical Engineering and Computer Science

1965 - 1973 — Technion IIT (Israel Institute of Technology) Haifa, Israel.
During M.Sc, Dipl. Ing. and D.Sc. study/research periods:
Assistant and Instructor - Faculty of Electrical Engineering.
During the entire 8 years period –
A. Laboratory instructor for the second, third and fourth year students in the electrical engineering and electronic circuits laboratories.
B.Class exercises on the subjects of electronic circuits and semiconductor electronic materials and devices.
Main duty in the last 5 years (1967-1973) - in charge of the Electronics Circuits Laboratory, supervising the assistants in the operation of the laboratory and instruction of the students.
Supervising 4th year student's laboratory projects

1957-1961 — Electronics technician and instructor-following technical high school graduation (majored in Electrical Technology),1956 - attending premilitary Air Force Technical School, Haifa, Israel for one year (August 1956 - August 1957) for training as a radio technician.
During regular military service (Aug.1957 - Aug.1963) served as electronics technician in the Central Air Force Radio Repair and Maintenance Laboratory for one year. Then joined the Air Force Technical School at Haifa, and served as an Electronics Instructor for Radio Technicians (Oct.1958 – July1961). Professional rank was Grade 12, which was the highest professional degree for radio technicians at that time (1961). Granted by the air force a Leave of absence for academic studies at the Department of Electrical Engineering, Technion, Haifa, Israel. Following termination of regular military service

at 1963, served as electronics technician and instructor in the Air Force during annual reserve service up to 1986. During the entire period at the Air Force, became acquainted with methodical approach to trouble-shooting techniques, maintenance and testing of radio receivers and transmitters as well as other electronic equipment and with diversified instrumentation and measuring equipment.

8. RESEARCH ACTIVITIES

I. Semiconductor based Optoelectronic Materials and Devices

Monolithically Integrated Silicon Light Emitting Devices (SiLED`s) Inventions, Research and Development *(EXTANDED DESCRIPTION)*

The focus in this summary is the original work culminating in a comprehensive approach for the *practical realization* of *cost-effective* single crystal Silicon Light Emitting Devices (Si-LEDs).

Background: The phenomenon of light emission from silicon junctions, which was known from the early fifties of the last century, was treated until recent years, mainly as a curiosity or at best as an interesting physical phenomenon. Being an *indirect bandgap material*, single crystal silicon (Si) was rejected as a practical light emitter from the start due to its inferior electrical to optical conversion efficiency, by comparison with that of III-V materials which presently compose most of the LED's and emit high optical output. During my Doctoral work(1968-1972), I have observed during my experiments in the laboratory this weak light emission and used it in relation to my research on breakdown mechanisms in silicon devices. Later on I have published my findings on the subject. In the following years, I have thought of ways to transform science to engineering on this subject, by converting this physical phenomenon into a practical working device, i.e, producing practical Silicon Light Emitting Devices (SiLEDs), to be used as components in electronic systems. In 1991 I was invited to the Department of Electrical and Electronic Engineering at the University of Pretoria, South Africa. I have noted that they have an excellent microelectronics laboratory as well as manpower to run it. I proposed to Professor M.Du Plessis which was the head of the laboratory to start a research aimed to produce practical SiLEDs, based on my knowledge on this subject. Professor Du Plessis was at first uncertain about it since he never heard until then that silicon emits light. However, after I experimentally demonstrated to him in his laboratory, on a Silicon PN junction that was fabricated in his laboratory that light is indeed emitted under appropriate operation conditions from his device, he was convinced. As a result we started together the project. Later on Professor L.W.Snyman joined the research. The collaboration which took place for about fifteen years was a very fruitful and yielded many original results, which were publishe in journals, conferences and yielded several patents(see CV). I was the leader of the project and it was performed under my guidance. A detailed summery of the project outcome is given below.

The work summarized below describes our achievements *in converting this physical phenomenon into a practical working device.*

From the start of this work there was a genuine need to overcome the problems resulting from the low electrical to optical conversion efficiency of Si in order to yield a solution

which is *decisively superior* to the other solutions for Si-LEDs fabrication suggested in the literature. Such suggested devices dealt for example, with quantum confinement and superlattices, erbium impurity in silicon, porous silicon and nanoparticles. Although some of them exhibited ~~a~~ promising performance, they were not generally adopted by the semiconductor industry because they necessitate *non-standard* fabrication schemes, some of which were elaborate and expensive, requiring *special production lines*. On the other hand, our work presents *an innovative approach, proposed and realized in practice by* ourselves*, enabling the fabrication of single crystal SiLEDs using the standard, conventional, fully industrialized IC technology "as is" without any changes of the processing and/or materials.* Consequently, it enables SiLED`s fabrication in the *same production lines* of the *presently existing IC industry* which is fully single crystal Si based. This means that the yield, reliability, and *price* of the above Si-LEDs are the same as the other Si devices integrated on the same chip. This was achieved by the utilization of the *physical mechanisms* leading to the light generation and emission, through the SiLEDs' doping levels, geometries, dimensions and well-thought-out design of standard processing sequences, in order to yield optimum performance for each intended use.These mechnisems involve high density excess carrier generation through ionization, which upon undergoing quantum transitions result light generation and emission. All this is done *by using standard IC design rules*. Special design considerations were made (within the existing rules) in designing the above SiLEDs structures, in order to ensure high reliability operation. The overall result is that SiLEDs can now be fabricated simultaneously with other components, such as transistors, on the same silicon chip, using the same masks and processing procedures. This also means that SiLED`s can now be *monolithically integrated* with their signal processing circuits. We actually used standard CMOS/BiCMOS fabrication, for the Si-LEDs fabrication, a fact which comprises *a major advantage* in itself. *The overall achievement of this work is that it enables the fabrication of on-chip, all-silicon integrated monolithic optoelectronic systems, by standard industrial means.* Since the fabrication of integrated Si detectors is already done routinely in ICs, the development of the above Si-LEDs, which involved patented inventions as well as journal and conference publications on our part, was a *crucial step* for the realization of the above optoelectronic systems. This is because this approach *enables an on-chip direct SiLED to Si detector optical coupling.* This coupling is highly efficient owing to three factors: (1) The *proximity* between the integrated devices resulting from their high packing density in the present VLSI technology (in the order of $>10^6/cm^2$).The resulting short distances between the SiLED`s to the Si detectors, largely compensate for the Si low conversion efficiency. (2) The *spectral matching* between the Si-LEDs and the Si detectors. In all the devices produced in this work, some of which are outlined below, the emitted light spectrum range typically between 400nm – 900nm, and peaked at about 650nm, i.e., it included *visible light* to a degree which could be seen by a naked eye (this wavelangth range well overlaps the spectral response of Si detectors). In fact, as is reported in one of our publications, we achieved an optical coupling between two chips using 1.5 meter long fiber optics. (3) Design of SiLEDs with *enhanced* light output emision, which is acheved through structuers which are descrbed below. The advantage of integrated optical coupling over the presently used electrical interconnections coupling within the chips, arises from the fact that optical coupling is faster. This advantage is specifically emphasized *in scaled down integrated circuits***,** which result in a reduction in the interconnections cross section. At a certain level of dimension reduction, this increases the interconnection electrical resistance and, despite the reduction in the capacitances, impedes the desired reduction in the RC delays. Our work eliminates this problem altogether through the utilization of the optical coupling. As the future devices within the chip will be further scaled down, the SiLEDs will be simultaneously scaled down in the same proportions due to the fact that the integration is predesigned and exicuted on the same masks. Another point relates to the fact that presently all the VLSI chips are made from single crystal silicon *only*. In this regard, the approach presented above which enables the ***monolithic*** integration of the

single crystal SiLED`s**,** makes *obsolete* altogether, the ideas of ***hybrid*** integration of the highly efficient III-V LEDs, or other non-crystaline Si light emitting devices, with single crystal Si chips, in order to obtain integrated optoelectronic systems. The size reduction trands of the present and future silicon IC`s, simply eliminates the possibility of external physical interconnection of III-V LEDs or non-crytaline Si LEDs, to single crystal Si chip , *leaving our solution as the only realistic option.*

Using the above described approach, we fabricated a range of single crystal SiLEDs, each with pre-ordained design properties. Some specific examples that demonstrate our pioneering contributions are: (1) *for the first time ever* – fabrication of *multiterminal* Si-LEDs. Two such transistor-like *families* were invented and patented, fabricated and characterized, *utilizing the inherent advantage of the power gain of active devices.* The light emission from these devices is *controlled by means of a separate low power consuming terminal or terminals.* One family is MOS-like Si-LEDs, in which an isolated gate is made across a junction. Its terminal controls the light emission properties of the device by affecting the electrical field in the space charge region of the revesed bias light generating junction. A second family is a BJT-like SiLED, in which a forward biased junction injects carriers into the space charge region of the revesed bias light emitting junction. Here too, the light emission properties are determined by means of a third control terminal which control**s** the carrier injection magnitude. *The concept of Multiterminal SiLEDs was first suggested by Professor Aharoni. They were realized for the first time ever in this project.* (2) *for the first time ever* – fabrication of a Matrix of dot light sources with four terminal gates which enable the control of the spatial distribution of the dots' light emission from the matrix surface.(3) through structural manipulations the operation voltage of the Si-LEDs was systematically adjusted to less then 5V, a value which is not readily attainable by using the standard IC processing and requiers spaciel design attention while using *only the convetional IC design rules*. This enables *a single power supply operation* of the all-silicon optoelectronic monolithic system. (4**)** Other, non-integrated single crystal SiLEDs were produced by us as discrete devices, which require higher operating voltages for special purposes. Accordingly, SiLEDs with various operation voltages and surface light pattern emission were tailored by design and fabricated according to specific needs. (5) Through *structural manipulations* and by devising *high current density regions*, the conversion efficiency of the Si LED`s was significantly increased. The work included investigation of various Si-LED original structures designed by us, with *enhanced* electrical-to-optical conversion efficiencies, realization of high electric field confinement silicon light emitting devices, rrealization of co-planar surface-controlled Si light emitting devices and realization of on-chip electrooptical light sources for optical coupling between Si-LEDs and Si-detectors**,** enabling production of optocoupler type circuits The fact that all the above were done by using *only* the standard CMOS/BiCMOS processing without any adaptation, well demonstrates our unique achievements. New area**s** of research in future modern optoelectronics are opened by the approach of close association with industrial processing. This approach present *far reaching technological and economical implications.*

It should be emphasized that these devices were made for the purpose of feasibility demonstration only. They illustrate the *generic nature* of this approach, i.e., that variety of other SiLEDs can be now produced as well. As a result each *SiLED can be now tailored in shape and/or structure and/or dimensions, by design, for a specific task* with regard to particular electrooptical circuit in order to satisfy a specific requirement. Both *single junction* and *multi-junction* silicon light emitting devices were realized, some of them are described below:

1. **Two – terminal Si-L.E.D`s**

   Verity of devices were made, including-

A. Concentric rings/centroid Si-L.E.D- light is emitted by utilizing surface assisted field emission ionization process that occurs laterally between concentrically arranged highly doped n^+ shallow junctions rings and a p^+ centroid, which are coplanarly arranged with an optically transparent Si-SiO_2 interface. Such an arrangement yields high current density and light intensity, from 20micron diameter of chip area, at the center of the device.

B.Seven segment Si-L.E.D – designed for numbers display.The structure of this device included relatively large light-emitting segment areas. Accordingly, a special design was made in order to ensure uniform light emission from the segments. Its operation is based on impact multiplication of excess carriers.

C.Circular SiLED for Chip to Chip Optical Fiber Coupling-Our approach is suitable not only for optical coupling between circuits within the chip. It is useful for a short distance optical coupling via optical fiber between chips located within the same instrument (computer for example) as well. A 60μm diameter SiLED was fabricated and its output light signal was transmitted to a chip which contained Si detector, located within a distance of 1.5 meter, yielding clear detectable electrical output.

2. Multiterminal Si-L.E.D`s

The two terminal Si-L.E.Ds present two major disadvantages (a) the light intensity (Li) is controlled by a relatively high reverse current, thus *loading* the driving circuits. (b)Li- is *linearly related* to the operation current, thus complicating signal-processing operations, such as signal mixing, for example. These two problems are *completely solved* by the realization of multiterminal SiLEDs, which in addition present other operational possibilities as well. The B.J.T-like SiLED provides a solution to (b) and the M.O.S-like Si-L.E.D`s provides a solution to both (a) and (b). *The concept of Multiterminal SiLEDs was first suggested by Professor Aharoni. They were realized for the first time ever in this project.*

A.**Three terminal B.J.T-Like Injection type SiLEDs** - The operation principle of this SiLED type is based on electronic coupling of two P-N junctions. One junction is forward biased, injecting free carriers into the high electric field space charge region of a reversed biased *wedge shaped junction*. This junction operates in the impact ionization multiplication mode. As the injected carriers move in the high electric field space charge region, high-density carrier multiplication takes place. These excess carriers undergo energy levels transitions, generating light. Due to the wedge shaped junction, the local current density there is high. This results high intensity of light emission, which can be several orders of magnitudes higher then that emitted from a single junction two terminal SiLEDs described above.

B. **Four Terminal B.J.T-Like Injection type SiLEDs** – This SiLED structure contains four implanted regions into P^- substrate, each with its external terminal. Its operation is similar in principle to that of the three terminals SiLED described in (A), but contains additional two light enhancing features. The first is that the structure of the reversed biased PN junction includes a needle-like shape at its edge pointing towards a forward biased PN carrier-injecting junction, which is located directly opposite to this junction, in front of the needle. This arrangement enables higher current density at the needle vicinity, and considerably higher light emission. The second is that the other two junctions are P^+P^-. They are located in a symmetrical fashion, diagonally to the reversed biased junction. Usually their

terminals are connected, so they operate under the same voltage. A voltage supply between their combined terminal and the reversed biased junction terminal is used to symmetrically inject carriers to the reversed biased junction controlling the amount of excess carrier multiplication in the reversed biased junction, thereby controlling the amount of emitted light intensity. They also add to the enhancement of the light emission by a *focusing action* on the injected carries from the forward biased PN junction, which are moving towards the reversed biased junction. This SiLED yielded the *highest light output* with respect to our previous SiLEDs or to any single crystal SiLED reported in the literature, following our work.

C. **Three terminal TRANSLED (Transconductance Silicon Light-Emitting Device)-** A novel three terminal M.O.S-like structure was fabricated, which enables the control of both the spatial light pattern emitted from the device surface, and the light output intensity, by means of an insulated gate voltage (V_G).Both the drain current-voltage I_D-V_D and I_D-V_G characteristics were determined. In addition, the light intensity (Li) was found to be a linear function of I_D, and the Li-V_G relation was accordingly found to be similar to the I_D-V_G characteristics. Depending on operating conditions, specifically the combination of the load line and V_G, the light pattern can be changed from an optical line source to two point sources (or both) and the emitted light intensity can be determined to be either a linear function, or a *quadratic function*, of V_G. The insulated gate solves the driving circuits current loading problem, and the non-linear Li-V_G relation enables a range of electrical to optical signal processing operations (mixing of several input electrical signals into single optical light output, for example).

D. **Four terminal Silicon L.E.D Matrix-**Fabrication of an array of a14x14 light emitting dot matrix on a Si substrate. The device is a M.O.S based structure, a fact that enables the control and modulation of both the light emission intensity from the dots and the spatial distribution of their light over the matrix area by the gates voltages, which are applied via four contacts. Unlike two terminal Si- LED`s, the light intensity emitted from the matrix devices is a non-linear function of the applied gate voltage, enabling a range of signal-processing operations.

All the above devices were designed and realized by using standard 0.8 micron, 1.2 micron and 2 micron CMOS and BiCMOS processes and with no modifications to the processes. The SiLEDs processing was performed according to our design. All the above structures are *cost-effective*, i.e. their prices are similar to those of the transistors fabricated simultaneously on the same silicon chip.

Other Light emission Experiments

A. Investigation of light emission from self-fabricated striation-dominated silicon junctions. Modelling of the influence of crystal defects within the striations on the fine details of the emitted spectrum at various operating currents. Study of the changes of light surface coverage and current density distributions over the junction's emitting surface as a function of operating current. Determination of the relation between the integrated emitted light intensity, light area coverage and reverse current. Determination of the dependence of the emitted light spectrum on the reverse current. Determination of the changes in λ_p (the peak emission intensity wavelength) as a function of reverse current.

B. Light emission in self-fabricated epitaxial p-n junctions, operating at high reverse voltages and currents. The determination of the relation between the light emission intensity and the pre-secondary breakdown junction behaviour.

ITO/InP Photovoltaic Devices
(EXTANDED DESCRIPTION)

Research and development activities regarding (Indium-Tin-Oxide)/(p-type Indium Phosphide) photovoltaic devices (ITO/InP PVD's) were conducted. These activities involved an extensive fabrication of the PVDs by Professor Aharoni.

The advantages of InP based PVD's over Si and GaAs PVDs are:(1) the InP exhibit low surface recombination velocity which results low surface current, yielding less losses of the conversion efficiency.(2) They exhibit higher resistance to gamma ray radiation. (3) They also exhibit self annealing capabilities of the radiation damage. The last two facts make InP based photovoltaic devices preferable potential candidates for the specific purpose of *space applications in hostile environments*, (4) Finally, the relative ease in which the InP surface can be passivated is an attractive factor from device fabrication point of view.

ITO&PVDs Characterization

Light I-V performance was determined by the PVDs exposure to calibrated solar simulator with standard integrated light power density. Their spectral response was determined by measuring the quantum efficiency (QE), using an automated filter wheel system. Their QE were determined both with and without white light bias. Temperature dependence of the short circuit current (Jsc), open circuit voltage (Voc), fill factor (F.F), optical to electrical conversion efficiency (η%), maximum power output (Pmax), current and voltage at maximum power point (Jmax, Vmax) were determined as well. Three major points, which affect the PVDs performance, were observed:

1. The measured conversion efficiencies, of the PVDs were not notably affected by the different InP substrate doping concentrations.

2. The value of the oxygen partial pressure introduced to the growth chamber during the ITO film deposition, clearly affected the performance of the ITO/InP PVDs. Our measurements on the ITO films have shown that the amount of oxygen incorporated in these films affected their composition which in turn affected their optical, electrical, physical and material and structural properties. This results *significant variations* in the PVDs conversion efficiencies due to the differences in the intensity of the light transmitted into the underlying PVDs junctions.

3. Correcting for the ITO optical losses, it was found that *the PVD's internal junction quantum efficiencies(QE) were unaffected by the ITO properties, all exhibiting the same high value approaching 100%.*

(1) and (3) imply that *the main factor, which determines* the ITO/InP PVD's *performance, is the ITO film properties*. The ITO films thicknesses of the produced ITO/InP PVD's were measured by an ellipsometer. Their optical constants were measured by a spectrophotometer. The carrier density and mobility were measured by the Hall method. ***The optical constants of the ITO films were found to vary significantly across the solar spectrum with (1) oxygen partial pressure introduced to the growth chamber during film deposition, and (2) film thickness.*** The first is due to a change in the density of the conduction electrons, i.e, at larger oxygen content in the ITO film, the film behaves more like a dielectric, with larger real and smaller imaginary parts of the refractive index. The real part of the refractive index varies significantly as a function of the radiation wavelengths (ranged between 400nm to 2400nm), as well as for different Oxygen partial pressures. This means that the intensity of the light transmitted into the InP depends on the ITO deposition conditions, *which implies that the ITO*

film optical properties can be tailored in a wide range for obtaining the desired results through the Oxygen partial pressure.

The ITO films resistivity (measured by four point probe) was found to increase *linearly* with the oxygen partial pressure. Measurements of the electronic properties showed that the rsistivity (determined by four point probe), increased *linearly* with Po_2 .The free carrier mobility decreased moderately slowly and at the same time the free carrier concentration showed stronger monotonic exponential–like decrease with increasing Po_2. Both were measured by the Hall method. The decreasing trends in the carrier concentration and mobility are in agreement with the simultaneous increase in the measured resistivity. This data indicates that IBS deposited ITO films transport properties *can be optimized to become near ideal,* by their deposition at the low Po_2 range where both carrier concentration and their mobility are high.

ITO physical properties were determination by optical means. The optical bandgap was determined from our optical data to be 3.84eV. It was also found that despite the fact that our ITO films are two orders of magnitude thinner than the skin depth (about 5μm at 1μm wavelength), some of them did followed Drude's theory. Accordingly, from N and k measured data for these films the real and imaginary parts of the permittivity were calculated, enabling to obtain the plasma frequency and the effective electron mass, to be $m^*=0.37- 0.42m_e$, were m_e is the electron rest mass.

X- ray Photoelectron Spectroscopy (XPS) measurements were carried out on ITO samples, with *changes made only in* the Oxygen partial pressures (Po_2) in the gas phase during their deposition, in order to correlate Po_2 to: (A) the resulting *composition* of the respective films, in terms of atomic concentration percentage of the In, Sn, and O elements, and (B) the resulting *bonding* of the Oxygen atoms to the In and Sn atoms in these ITO films. The three XPS core level spectra (i.e, N(E)/E vs. binding energy(eV), corrected for inelastic backscatter) for the $In3d_{5/2}$, $Sn3d_{5/2}$, and O1s components was obtained. *Compositional analysis* yielded their *atomic percent concentrations* of Indium/Tin/Oxygen in these samples as a function of Po_2. The analysis showed that part of both the Indium (In) and the Tin (Sn) are chemically bonded to the Oxygen. The lack of such bonding constitutes an *Oxygen Vacancy [OV]*, which acts as a *Donor*. Since according to the our results, the atomic percentage of the Indium is much higher than that of the Tin, ***the Oxygen vacancies in the indium bonding (In-O bonds) are the dominant contributors of the free carrier concentration, which determine both the optical properties as well as of the electronic transport properties of the ITO.*** Our experimental values were compared to the theoretical estimates of the oxygen content, showing that *the IBS ITO deposited films become increasingly stoichiometric in films which were grown with higher and higher Oxygen partial pressures*. Similar procedure was carried out for the $Sn3d_{5/2}$ component, showing *that the excess Oxygen introduced to the growing films during their deposition is bonded predominantly to the Sn atoms in the ITO structure.*

Auger electron spectroscopy (AES), analysis was qualitatively in agreement with the XPS analysis, however it yielded in this case *a better agreement with the electronic data* then the XPS. The analysis show that as Po_2 increases *an increasing oxidation level of the Indium, in the respective ITO films take place.* Further analysis *indicated a clear increase in the Indium oxidation concentration, approaching stoichiomertry as the Po_2 value in the ITO films is higher.* These AES results render themselves to a *self-consistent correlation between the electronic properties, and the compositional data of the IBS deposited ITO films in as much Po_2 is concerned.* The decrease in the carrier concentration in these films, as Po_2 increases, correlates well with the increase of the Indium oxidation concentration with Po_2. The resulting concentration in the *Oxygen vacancies [OV]* decreases with Po_2. Since Oxygen vacancies act as donors, the decrease in their concentration with the increase in Po_2 is in accordance to the measured decrease in the carrier concentration with Po_2, *indicating that the free carrier*

concentration (n) is directly proportional to the Oxygen vacancy concentration [OV]in the In-O bonds of the various ITO films.

Post deposition annealing experiments were carried in order to investigate the dependence of the free carrier concentration, and mobility on the *structure* and *composition* of the IBS deposited ITO films grown in various Oxygen partial pressures (Po_2). **Electron Diffraction**, **X-Ray Diffraction**, as well as **Conversion Electron Mössbauer spectrometry (CEMS) measurements** indicated that the *unannealed* ITO films stricture is *microcrystalline* (In_2O_3). On the other hand, their annealing above 250^0C in air or in forming gas in vacuum at 350^0C, increases both their crystal size and the extant of their orientation. **Transmission Electron Microscope (TEM)** data of as deposited ITO films, revealed the existence of few widely spaced nucleation sites of about 10nm within the microcrystalline background. In situ TEM analysis revealed that the grain growth will develop from these sites, giving rise to the formation of crystallites up to1µm in diameter.

Other Photovoltaic Devices

A. Fabrication of ion implanted Si solar cells for high light concentration. Gettering of heavy metals' unwanted impurities by Ar implantation on the Si substrate back surface. The determination of the progressive increase in carrier lifetime within the Si substrates with Ar implanted dose, using photovoltage decay measurements. Dark and light I-V measurements.

B. Fabrication, process development, electrical and optical characterization of GaAs photovoltaic devices utilizing OM-CVD. A.R. coating by anodization. Electroplated gold contacts.

Fabrication of on$^+$p/p$^+$ GaAs photovoltaic devices (OM-CVD and MBE grown)with various top layer thickness and experimental study of the influence of top layer thickness on their performance.

In B and C - dark, light I-V and C-V characteristics and spectral quantum efficiency measurements were performed. Measurements of the effects of solar cell temperature on the above parameters were made.

Organometallic Chemical Vapor Deposition (OM CVD) For GaAs Photovoltaic Devices

GaAs solar cells are composed of thin P- type and N-type GaAs layers for photovoltaic active junction formation. The requirement for thin layers which contain certain thickness, doping type, and doping concentrations, arises from design considerations for optimized optical to electrical conversion efficiency. The device operation is sensitive function of the above layer parameters. Accordingly, precise control of the layer parameters during its growth is essential for optimized photovoltaic device performance.

A. Pure GaAs layers were grown using TMG (Trimethylgallium) and Arsine (AsH_3). Doped GaAs layers were grown by adding the following agents-growth of N layers (by adding H_2Sin the gas phase) and of P layers (by adding D.M.Z. in the gas phase). The layers were grown on GaAs and Ge substrates, at atmospheric pressure. Growth in various temperatures, gas flow rates, and Ga/As ratios in the gas phase was performed for optimization purposes. The carrier mobility's and concentrations were determined. PN junction formation and characterization.

B. Low pressure OM-C.V.D. by modified Atomic Layer epitaxy (ALE) of single crystal ZnSe on GaAs to form N^+/N junctions. Measurements by X-ray diffraction, I-V characteristics and spectral response. Study of the junction band structure.

C. Low pressure OM-CVD of thin ZnSe layers by Modified ALE on Si Substrates using various deposition conditions. Characterization by using X-ray diffraction, SEM, photoluminescence and Electron Microprobe.

Development of New Techniques for Spectral Tuning of LEDs

Wavelength tuning of III-V LEDs emitted light spectrum is known to occur through changes in temperature, hydrostatic pressure (by liquid) and magnetic fields. Their effect on the spectral response is based on the changes of the semiconductor forbidden gap (Eg), which they cause.

In this work, a new technique for ***wide-ranging spectral tuning*** of commercial GaAs LEDs, was developed. The dominant mechanism, which is based upon, is ***surface effects*** of the LED's semiconductor. This technique however is applicable to other semiconductor light emitting sources as well. It was done through immersing the LEDs in various ***gases environments*** (air, neon, nitrogen) at ***various pressures P,*** which started at 10 atm. and then decreased by steps down to a vacuum of 10^{-6} atm. level. In all the experiments, at each step of prssure change, a rlaxation time was allowed in order to reach to a stady state. The resulting peak wavelangth λp shifts are ***logarithmic*** with pressure and vacuum alike, exhibiting the same negative slope S on semilog plane of pressure vs. emitted peak wavelangth, i.e, as the pressure increases the peak wavelangth becomes shorter. The affect of increasing the forward operating DC current (I) resulted a decrease (less negative) of the slope S, as well as simultanous increase in the emitted light intensity, adding another conrroling factor for the spectral tuning. It was found that the ***entier spectrum is shifted with the operating current*** towards the ***longer*** wavelangths as I increased. This shift takes place everywhere across the spectrum, but it is noted mainly at long wavelangths.The **degree of the shift** towards the longer wavelangths increases with the operating current as well. The bandwidths Δλ were affected by P no more then 20%. Higher operating currents yielded larger band widths. The above spectral changes exhibit different values at different gas enviorements. The resulting wavelength shifts is continuous, repeatable, reversible, controllable, and non-destructive. Operating the device with constant current level ***pulses*** at a rate of 450 pulses/sec, at different pressure/vacuum conditions, rsulted in general no no spectral shifts up to certain duty cycle 0.4% ,i.e 10μsec), and then exhibited a ***linear increase in the spectral shift*** Δλ as the duty cycle increased.

Nuclear irradiation (in air enviorement) of very shallow junction GaAs commertial LEDs by ***γ-ray***, yieled changes in their optical emission performance as well. These changes are ***much more noticble*** than those which tooke place in deep junctions GaAs LEDs reported in the litrature. In order to avoid effects of enviormental impurities, the spectral measurments were taken with the LEDs immeresed in 1atm. Ne enviorment. ***An increase in the peak wavelangth λp*** took place following irradiation. λp values were measured in steps up to dose irradiation of 13 Mrad. The resulting shift was from 905nm to 925nm. This shift of 20nm is larger then those reported for deep junctions LEDs. Another effect of the irradiation was the ***emission spectrum nerrowing*** near its maximum. For example, the width of of the spectrum at 88% of its maximum intansity for operation current of 125mA prior to its irradiation was 25nm and it nerrowed to 19nm and 15nm following irradiations of 1.35Mrad and 12.75Mrad respectivly. The resulting ***attanuation*** of the overall emission spectrum was only ***slightly***. These changes are regarded as ***improvements*** in the shallow junction LED emission parameters since they are ***suiteble for optical communication***. The

above increased peak wavelangth is desierble in GaAs devices to decrease fiber material dispression. The bandwidth nerrowing is desierble as well (less model dispression). This is achieved while exhibiting no noticble disadvantages.

All The above LEDs behaviour were explained by new models spcifically developed for each case.

Optical Properties of RF Sputtered Amorphous Silicon

A. Amorphous silicon (α-Si) sputtering on glass substrates. The determination of the influence of argon partial pressure on the deposited α-Si properties such as dark conductivity and photoconductivity as a function of sample temperature. Optical transmission measurements for the determination of the refractive index as a function of wavelength, and
of the ratio of hydrogen/argon partial pressures (P_H/P_A). The determination of the bandgap E_g as a function of P_H/P_A.

B. Assembly of an in-situ mass spectrometer with a sampling chamber, in the RF sputtering system for the determination of unwanted impurities in the gas/plasma phase during sputtering. Calibration curves for the various gases for the above measurements. Determination of impurity types in the solid layer by electron microprobe.

BANDGAP ADJUSTMENT OF C.V.D GROWN Si-Ge HETEROEPITAXIAL LAYERS FOR OPTOELECTRONIC DEVICES

As a part of my Doctoral work at B.G.U- pioneering in Israel the subject of atmospheric pressure Chemical Vapor Deposition(C.V.D) of thin films Silicon-Germanium (Si-Ge) heroepitaxial layers growth. The first to design, build, calibrate and operate the C.V.D system in order to produce hetroepitaxial Si-Ge layers.
Since the bandgap (Eg) is a function of the lattice constant (parameter) it can be changed to a predetermined value by changing the lattice constant of a crystal by controlling the Ge/Si ratio of the grown crystal. Thus, the Eg value can be tailored to accommodate the requirement for a specific optoelectronic device (infrared detector for example). This work involved designing, building, calibration and maintenance of two epitaxial growth systems from the vapour by CVD, for Si, Ge and their solid solution.
Specifically:
A. Growth of high quality Si-Ge heteroepitaxial layers on Si substrates, by reduction of $SiCl_4$:$GeCl_4$ (gas phase) in hydrogen carrier gas atmosphere. Study of the influence of growth parameters on layer quality and defects. Study of the growth processes. Generating transfer curves of Ge/Si ratios in the gas phase to the Ge/Si ratios in the solid phase. Determining the changes in the lattice constant (X-ray diffraction) as a function of layer composition, characterization of various defects.

B. Growth of high quality Si-Ge heteroepitaxial layers on Si, sapphire (Al_2O_3), and Ge substrates, by pyrolytic decomposition of SiH_4:GeH_4 in Hydrogen and/or Helium carrier gas atmospheres. Growth was performed in various temperatures, chemical reactant concentrations and flow rates. X-ray study (diffraction, rocking curves) of the degree of preferred orientation of Ge on Si, and the morphology of Ge layer surfaces, as a function of deposition time and temperature. Optimization experiments.

Optically resolving crystalline/amorphous transitions in ion implanted single crystal silicon
(EXTENDED DESCRIPTION)

A non-destructive powerful optical diagnostic tool was developed in order to detect and identify the process of material state transition which takes place within ion implanted electronic grade single crystal silicon substrates during electronic and optoelectronic device fabrication. In particular, (A) how to verify when *full amorphization state* is reached as a result of the high energy ion dopant atoms implantation, (B) how to verify when full *recrystalization state* is restored by epitaxial regrowth progression as a result of the subsequent annealing, (C) to continually monitor and detect the transition between these material states which takes place during the implantation or annealing. These are important determinations since the quality of device performance is entirely dependent on them. The solution described below is based on *reflectivity measurements* of the Si implanted wafer. This approach is entirely unlike the implanted material state determination made in the present silicon device fabrication technology, i.e, by examining the final device operation, by external current-voltage measurements. This present approach requires several trail and error experiments for each new developed device. The main disadvantage of the present approach is that the real *internal* situation of the material state during the implantation and subsequent annealing is externally inferred, *but not actually known, unless a destructive analysis (such as TEM - transmissin electron micriscopy) is performed*. The description below is subdivided into (1) the research part, and (2) the resulting product.

(1)Discrete Measurements

Two groups of implantations were made. In the first - a series of single crystal electronic grade Si substrates each implanted with different dose (N), keeping the implantation energy (E) as well as the other implantation parameters constant. For this series, following implantation termination, the reflectivity (R) of each implanted substrate was measured by the ratio of the incident and reflected beam of an He-Ne laser (632.8nm wavelength) and a graph of R vs. N was obtained were *each point* represents the reflectivity of a *single sample*. Three regions were identified on the above R vs. N graph, regardless of the ion species that was implanted. For example when $^{31}P^{+}$ is implanted at 50KeV, then at the low dose region (A) were N< $4x10^{14}$ cm^{-2}, only small changes take place in the reflectivity, i.e, it was about 33.6%, a value which is close to the reflectivity of single-crystal (111) Si at this wavelength. This means that the implantation damage within the implanted substrate is still small, and the crystal order is largely maintained. As N is increased ($4x10^{14}$ cm^{-2}<N< $8x10^{18}$ cm^{-2}), a second region (B), is reached, were a *large and steep monotonic rise in R is clearly seen* which ranged from33.6%,up to a maximum reflectivity of 42.5%. TEM (Transmission Electron Microscopy) images clearly demonstrated that this region is characterized by the formations of many small "bubbles" that are images of small zones of *amorphous* silicon. The number and size of the amorphous zones are changed as the implanted dose (N) was increased. As N is further, increased within region B, partial coalescence between them occurs, forming larger and larger discreet amorphous zones, giving rise to the above steep increase in R. In such a case, R in this region represents some average value of amorphous/crystalline material mixture for each implanted sample. At the end of this region (N>$8x10^{18}$$cm^{-2}$ and R= 42.5%), a new region (C) is formed, where the reflectivity remains at this high value, exhibiting only a small decrease in its value with increasing N. At the beginning of this region, a *full coalescence* takes place between the small amorphized regions, a fact which results a *thin continuous amorphous layer* on the top surface of the single crystal substrate. As N further increases, the *thickness* (Wd) of the amorphous layer is increased as well. If the above experiment is performed at

higher implantation energy (E), the location of the amorphous layer is shifted deeper to just below the Si substrate surface, i.e it becomes "buried", so it is bounded from above and below by a single-crystal silicon. The amorphous layer depth (Xd) below the substrate surface increases with the implantation energy, however the general shape of the R Vs. N in these cases are maintained regardless of E . The second set of experiments was made by keeping the implanted dose (N) as well as other implantation parameters constant, while implanting each substrate at deferent dopant ion atom energy (E). Again, following implantation termination, the reflectivity (R) of each implanted substrate was measured. The resulting Rvs.E graph were *each point* represents the reflectivity of a *single sample*, clearly exhibited *oscillations*. That is, R raised and fell at periodically as E increased. This is because as E was increased both Wd and Xd increased, and the resulting two layers (C-Si/α-Si) ,or in case of higher E - three layers(C-Si/α-Si/C-Si) gave rise to constructive and destructive interference of the reflected light. A theoretical multilayer optical model of the above (C-Si/α-Si/C-Si) structure was made and analyzed using matrix methods. The resulting theoretically generated Rvs.N curves were similar to the measured curves. The value obtained for the complex refractive index of the amorphous layer was n= 4.4-i0.67, agrees very well with that quoted in the literature for α-Si. They showed that in order to obtain fully amorphized continues layer the density of implanted spices in the Si substrate should exceed $2.1x10^{19}cm^{-3}$ (which is close to the measurd value of $8x10^{18}cm^{-2}$) , which accordingly constitutes the threshold dose for amorphization. This way, reflectivity measurements of single-crystal Si, implanted with phosphorus, boron and argon, using various doses, energies and beam current densities were performed. In general, they exhibited similar characteristics described above, but with different numerical values for each implanted species.

(2)In-Situ Measurements

The determination of the state of the implanted Si through optical measurements as described above suffers from a serious disadvantage, i.e, the construction of the Rvs.N and/or Rvs.E graphs *require many implantations*, each, which yield one point on the respective graph. This means an investment of time and effort. Moreover, data scattering take place since it is difficult to maintain all the implantation parameters the same for each implanted Si substrate. Accordingly, an *in-situ* reflectivity measurement system was constructed and placed within the ion implantation system. This way, the reflectivity of the ion implanted Si could be measured continusly *during* the ion implantation. This way, *entire* R vs. N and/or R vs E graphs can be obtained from a *single Si substrate* a fact that saves a lot of time and effort. The fact that the graphs are *continues* and obtained from a single substrate eliminates altogether the scattering problem mentioned above. However, the most important benefit from this approach is that due to the graphs continuity and lack of scattering , new information was revealed such as points of maximum, minimum and infliction, which exist near the transition segments between the three regions described above. These points were not seen in the graphs obtained by many samples. They proved to be important since they provide new information regarding critical implanted Si material state parameters. Such parameters are the threshold dose which initiates the change of the material phase (single crystal) within the silicon substrate as well as the amorphization dose from which a whole layer below or at the surface of the implanted silicon becomes amorphised. These points also enabled the determination of the work (or overall invested energy) required to attain each of the above critical stages. This in situ reflectivity measurement approach presents an important improvement for both research and practical applications with respect to previous approaches since it is *much more accurate, fast, inexpensive, non-contact and non-destructive, and provides information during real implantation time, a fact that enables real-time process control.* In addition, by employing raster scan of a light beam over the implanted Si wafer, the lateral *implantation uniformity* can be determined.

Optical Emission Sepctroscopy For Plasma Properties Investigation

Both electronic and optoelectronic semiconductor devices employ thin transparent insulating films such as silicon oxide (SiO_2) or silicon nitride (Si_3N_4). Usually these films are produced by employing thermal (900 ^oC - 1100 ^oC) *molecular based reactions* of oxidizing and nitridizing *molecules* with the silicon substrate. A new approach employ microwave-excited (frequencies of 2.45GHz or 8.3GHz) high-density ($>10^{12}$ cm^{-3}) plasma system, which utilize low bombardment inert gas ion energies (<7 eV), low plasma potential (<10 V), and low electron temperature (<1eV), in order to obtain the above films. This method employs a *radical based reaction*, of the oxidizing and nitridizing *radicals* with the silicon substrate. The radical reaction enables the above films growth at 400°C silicon substrate temperature. In order to grow Silicon Oxide (SiO_2) films an inert gas (one of He, Ar, Kr, and Xe) is mixed with O_2 is employed, for plasma generation. Silicon Nitride (Si_3N_4) films were grown by using Ar/N_2, $Ar/N_2/H_2$ and Ar/NH_3 gas mixtures for plasma generation. Both films types were grown in a vacuum chamber using different partial and total pressures of the above gases.

Important information regarding the SiO_2 and Si_3N_4 films growth mechanisms, specifically the growth rate, can be obtained by optical means, i.e, by *optical emission spectroscopy* of the light emitted from the plasma, during the film growth. Optical data is obtained from the oxidizing (Oxygen) and nitridizing (nitrogen or NH_3) *ions* and *radicals* within the plasma. Each such oxidizing and nitridizing ion and radical emits light at a *characteristic wavelength,* during the plasma excitation, a fact that *enables its identification.* The light emission *intensity* at each wavelength provides a measure of that specific species density in the plasma. Accordingly, the light intensity of a specific species is dependent on the partial pressure of that specific gas as well as on the total pressure of the all the gases in the plasma. Therefore, the emitted light *intensity* of a specific radical provides *a measure of the growth rate* of the specific film formed by that radical reaction. The optical emission wavelength and intensity measurement is done by externally placing the detector of an optical spectrometer (Otsuka Electronics, IMUC-7000) at the view port of the growth chamber.

Few examples of the above plasma species light emission utilization for the determination of various film growth rates mechanisms are given below:

1. In order to understand the experimentally obtained dependence of the SiO_2 growth rate on the total gas (Ar/O_2) pressure in the plasma chamber, both the Oxygen radical (O^*) optical emission intensity (at 777nm) from the plasma, and the ion flux density were measured as a function of the total pressure. The results show that the ion flux decreases and at the same time the O^* optical emission intensity (777 nm) increases as working pressure increases. Since the oxidation of the silicon is governed by both the ion flux density and the O^* generation, the combination of the above provides an explanation to the obtained dependence of the SiO_2 growth rate on the total pressure.

2. In order to understand the dependence of the growth rate of Si_3N_4 film (grown by Ar/N_2 plasma) on the N_2 partial pressure, the nitrogen ion N_2^+, optical emission intensity (at 391 nm) was detected from the plasma during film growth, as a function of the N_2 partial pressure (X%). In this case, in order to study the effect of the *microwave frequency* on the growth rate of the film the plasma was generated either by the 2.45 GHz or the 8.3 GHz irradiation into the growth chamber. The N_2^+ optical emission intensity radiated (391nm) from the plasma generated by the 2.45 GHz microwaves increases monotonically as the N_2 mixing pressure increases. On the other hand, the N_2^+ optical emission intensity of the plasma generated by the 8.3 GHz radiation is notably smaller than that of 2.45GHz plasma

optical emission intensity. It was noted that it exhibits a maximum at 25 % of N_2 mixing pressure. In both cases the results were compatible with the actual growth rate information.

3. In order to study the effect of H_2 partial pressure(X%) in the plasma on the growth rate of Si_3N_4 film (grown by Ar/N_2/ H_2 plasma), at 8.3GHz microwave radiation, both the NH radicals (NH)* at 336nm and N^+at 391nm optical emissions as a function of the H_2 partial pressure were measured. While, the N_2^+ optical emission intensity is low and strongly decreasing with (X%), a noticeable generation of $(NH)^*$ (336nm) is observed, which increases with the H_2 mixing pressure, indicating that the generation of $(NH)^*$ is inherent part of the film nitridation process.

4. In order to study the effect of the NH_3 partial pressure on the growth rate of Si_3N_4 film (grown by Ar/ NH_3 plasma), the $(NH)^*$ optical emission intensity at 336 nm as a function of the NH_3 partial pressure (X%), in plasma generated either by 2.45GHz or by 8.3GHz was monitored. The $(NH)^*$ intensity of both radiation frequencies increase linearly with the NH_3 mixing pressure. The $(NH)^*$ optical intensity of 2.45 GHz was notably larger than that of 8.3 GHz, indicating that the 2.45 GHz generates (NH)* more efficiently, a fact which enhance the growth rate at this frequency.

Other plasma parameters under various growth conditions were obtaind this way, yielding both important practical plasma and film growth mechanisms information.

II. Electronic & optoelectronic materials Processing and Development

Low Temperature Growth of Thin Transparent Insulating Films

Transparent insulating films are used in a wide range of electronic and optoelectronic devices. Usually such films are grown at high temperatures. Using the conventional growth techniques films such as Silicon Oxide (SiO_2), Silicon Nitride(Si_3N_4)and Silicon Oxinitride (SiON) require growth temperatures that range between 900°C to 1100 °C. For verity of reasons, it is desirable to lower the growth temperatures of these films. A comprehensive research achieved this goal producing highly reliable films at significantly lower growth temperature. This is achieve by two different newly developed methods:

1. Oxidation, Nitridation and Oxinitridation of Si surfaces atLow Temperatures(400°C), by Plasma Techniques

A vacuum system employing a Microwave-Excited (2.45 GHz ; 8.3GHz) High Density(>10^{12} cm^{-3}) inert gas (He, Ar, Kr, Xe) plasma , each mixed with oxidizing or/and nitridizing gases (O_2; N_2 ; N_2 / H_2; NH_3), was used for the growth of thin and ultra-thin, oxide(SiO_2), nitride(Si_3N_4)and oxinitride (SiON) insulating films, on Si surfaces, at low substrate temperature of 400°C. The typical values of the plasma potential, ion bombardment energy, electron temperature, and microwave power density used were 10V, 7eV, 1.3eV and 5w/cm^2, respectively. The experiments were performed in various partial and total pressures. The films obtained at 400°C in this fashion, yielded equal or superior integrity as well as growth rates, with respect to films grown by the conventional thermal techniques at 900°C.

2. Oxidation By Pt – WVG (Catalytic (Pt) Water Vapor Generator)

A newly developed WVG, fed by O_2 and H_2 gases, utilizes a platinum coated catalyst layer on an interior wall of a reactor, to produce and enhance instantaneously, at low reaction temperature ($350^oC – 400^oC$),a high density, stable supply of H_2O vapor at its output. The instantaneous $H_2 – O_2$ reactivity, enables a perfect control of the vapor composition, density and stability. Unlike conventional torch-like (pyrogenic) systems, which operate at high temperatures ($560\ ^oC$ - $800\ ^oC$), resulting in the generation of contamination, as well as safety problems, this low $H_2 – O_2$ reaction temperature, does not cause the generation of contamination, resulting in ultra-clean vapor. Since the vapor temperature is considerably below the oxidation temperature (unlike the torch vapor), *the oxidation temperature can be lowered* without affecting the Si substrate temperature uniformity. Lowering the growth temperature reduce the film's growth rate, enabling better control, specifically for the growth of ultra-thin gate oxides. SiO_2 films grown (at 750^oC) by the Pt-WVG were investigated, by utilizing them as gate insulators in M.O.S capacitors, exhibited high integrity properties. M.O.S.FE.T`s containing Pt-WVG grown (800^oC), as well as dry thermally grown (900^oC) SiO_2 gate insulators, exhibited *comparable* Current-Voltage characteristics but with improved reliability (Qbd).

III. Electron Devices Research and Development

Supper Clean Room Devices

Ion implanted N^+P junctions

1. Analysis of Silicon n^+p junctions produced in a Super-Clean Room predesigned and built for the research and development of future ULSI (Ultra Large Scale Integration) devices and circuits. It was found that the junctions`characteristics and performance are significantly substrate doping (N_a) dependent, through the position of E_t, the energy of the trapping centres. E_t was found to shift away from the middle of the bandgap as N_a increases, affecting the generation-recombination rates and related junction parameters. This shift is noticeable in this case owing specifically to the ultra clean production environment.

2. Comparative examination research of the performance of high-quality ion-implanted n^+p silicon junctions with varying N_a, annealed at high and low post-implantation temperatures. This was done since low-annealing (450^oC) temperatures, which in our case exhibited excellent characteristics, are important for the production of future ULSI circuits, enabling extremely shallow, steep profile junctions, reducing out diffusion effects and hence enabling the use of ultra-thin submicron epitaxial layers. The comparison to junctions of the same dimensions and processing but annealed at 1000^oC provided information regarding the difference in the transport mechanisms of the two cases. As a result, they demonstrated completely different performance trends. The analysis traced the above difference to the opposite shift of E_t as a function of N_a in the two cases.

Low temperature processing of M.O.S.F.E.T`s

In the following device processing, the drain/source ion implantation was made by the same system as the above described N^+P junctions. This implantation system is an ultra-clean, high vacuum system. In addition, due to the introduction of undoped Si wafers in strategic places within the system, undesired wall sputtering is minimized, resulting in only subcritical levels of metallic contamination. Since heavy metal atoms in the implanted Si disturb its recrystalization, their absence (or

lower concentration) enables lowering of the post implantation annealing temperature. In the following drain/source formation, 600°C post implantation annealing was used, resulting in excellent junction performance, i.e., low leakage currents, almost unity ideality factors, high reverse breakdown voltages etc. The carrier profiles have shown that the junction depths were 50nm for the Boron and 60nm for the Arsenic implantations respectively.
The M.O.S.F.E.T`s were fabricated on (100) Si substrates, as well as on (111) Si substrates. This is due to the fact that in System-On-Glass (SOG) devices, the poly Si includes various crystallographic orientations, specifically (111), as described below:

1. <u>M.O.S.F.E.T`s fabricated with (400$^{o}$C) gate oxidation</u>– Both P and N channel M.O.S.F.E.T`s were fabricated on the (100) and (111) substrates. For each device type, the gate oxidation was performed by employing the Kr/O_2 microwave-excited high-density plasma system described above, at 400°C. In addition, identical devices were fabricated, with conventionally grown dry gate oxidation at 900°C, as a reference. *The results have clearly demonstrated that the I_D-V_D and the I_D-V_G characteristics of each device type, fabricated with Kr/O_2 gate oxidation, were comparable to that fabricated with conventional gate oxidation.* In addition, it was found that *unlike* the case of dry gate oxides*, in Kr/O_2 gate oxides, the fixed surface state charge density (Qss), is only weakly dependent (practically independent) on the Si substrate orientation.* Combined with the fact that Kr/O_2 oxides exhibit *comparable or superior performance* (as described above), with respect to dry oxides, it is suggested that the Kr/O_2 oxidation technology bers a significant potential for ultra thin gate oxide formation in future ULSI M,O,S device fabrication.

2. <u>M.O.S.F.E.T`s fabricated with Pt-W.V.G (800$^{o}$C) gate oxidation</u> Both P and N channel M.O.S.F.E.T`s were fabricated on the (100) and (111) substrates. For each device type the gate oxidation was performed by employing the above described Pt-W.V.G system, at 800°C. In addition, identical devices were fabricated, with conventionally grown dry gate oxidation at 900°C, as a reference. *The results have clearly demonstrated that the I_D-V_D and the I_D-V_G characteristics of each device type, fabricated with Pt-W.V.G gate oxidation, were comparable to that fabricated with conventional gate oxidation*. Combined with the improved Qbd of the Pt-W.V.G films with respect to that of dry oxidation films, and with the advantages of this oxidation technique described above, it is concluded that this approach bers a potential for future device fabrication.

<u>**Other Electronic Devices**</u>

A. Fabrication of epitaxial transistors and diodes for the investigation of the influence of epi-layer thickness and dopant concentrations on their "Secondary Breakdown" properties.

B. Study of the input and output characteristics of regular bipolar transistors, which exhibited <u>negative differential resistance</u> when they were operated in the high voltage high current regions (avalanche mode). Study of fast avalanche transistor circuits.

<u>MEASUREMENTS</u>

The data obtained in the above research activities employed the following

measurement instrumentation:
Scanning Electron Microscope (SEM)
Electron Microprobe (WDS, EDS)
Laue
X-ray Diffraction
X-ray Photoelectron Spectroscopy (XPS)
Ultraviolet Photoelectron Spectroscopy (UPS)
Auger Electron Spectroscopy (AES)
Electron Beam Induced Current (EBIC)
Spectral Response Measuring Equipment
Ellipsometry
Double beam spectrometry (transmission and reflection vs. λ measurements)
Transmission Electron Microscope (TEM)
Photoreflectance
Photoluminescence
Conversion Electron Mössbauer spectroscopy (CEMS)
Atomic Force Microscope (AFM)
Gas Chromatography-Mass Spectroscopy (GC/MS)
Induction Coupled Plasma-Mass Spectroscopy (ICP-MS)
Secondary Ion Mass Spectrometry (SIMS)
Total Reflection X-Ray Fluorescence (TRX-RF)
Photo Emission Spectroscopy

9. MEMBERSHIP IN SCIENTIFIC SOCIETIES

1.Fellow-European Physical Society(EPS),2018.

2.Fellow-South African Institute of Electrical Engineers(SAIEE).

3. Fellow- Optical Society of America (OSA).

4. Fellow-The International Society for Optical Engineering (SPIE).

5. Fellow- American Physical Society (APS).

6. Fellow – Institution of Engineering and Technology (IET), (Formerly IEE),

7. Fellow – Institute of Physics (IOP).

8. Senior Member- Institute of Electrical and Electronic Engineers (IEEE).

9. American Vacuum Society (AVS).

10. Material Research society (MRS)

11. The Israel Association for Crystal Growth.

12. Israel Vacuum Society (IVS).

13. Israel Physical Society (IPS).

10. CERTIFICATED SHORT COURSE ATTENDANCE

1. Computer Applications Course - Ben- Gurion University, Beer-Sheva, Israel. February 27 – June 12, 2003. (26 hours).

2. Using OFFICE Course – A sherot training Centers. Beer-Sheva, Israel. (Certificate No.9958). 40 hours. 21/03/1999 – 23/05/1999.

3. Vacuum Technology Course - American Vacuum Society, (Short Course Executive Committee) Denver, Colorado, U.S.A., May 6 - 10, 1985.

4. Compound Semiconductor Materials and Process Technologies Course - Continuing Education Institute, Monterey, California, U.S.A., Feb. 4 - 7, 1985.

5. Surface Acoustic Waves Course - Rand Afrikaans University, Dept. Electrical and Electronic Engineering, Johannesburg, South Africa, Aug. 9 - 13, 1982.

6. Using Digital Electronic Computers Course – Technion Research and Development Foundation (Extension Division), Haifa, Israel. 50 hours, 21/03/1965.

7. Instruction Methods Course - Air Force Technical School, Haifa, Israel, Sept. 27 -Oct. 11, 1960.

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"Enhancement of Light Emission from Si PN Reverse Breakdown Structures by means of Current Density Confinement and by Insertion of Third Semi-conductor Bodies"
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