A New Method for the Determination of Carrier Lifetime in Silicon Wafers from Conductivity Modulation Measurements

Ussama A. Elani

***Abstract*—The measurement of dark σ_D, gamma-induced σ_γ conductivities and the expected conductivity modulation $\Delta\sigma$ in silicon wafers/samples is studied for developing a new technique for carrier lifetime evaluation. In this paper a simple method is introduced to find the carrier lifetime variations with the measured conductivity and conductivity modulation under dark and gamma irradiation conditions. It will be concluded that this simple method enables us to give an improved wafer evaluation, processing and quality control in the field of photovoltaic materials and other electronic devices.**

***Index Terms*—Silicon wafers, photovoltaic devices, conductivity modulation measurement, minority carrier lifetime, semiconductor materials quality**

I. INTRODUCTION

Electrical and electronic properties of semiconductor materials are normally required to be measured as accurate as possible. For example, bulk resistivity, sheet resistance, contact resistivity, carrier diffusion length and carrier lifetimes are needed for material modelling and manufacturing processes. The measurement of carrier lifetime in silicon wafers was studied in the past three decades. This parameter is still required to be determined accurately for new composites and nano-materials.

The conductivity modulation could affect the distribution of charge carriers available for conduction. Thus, the excess conduction loss can occur as conductivity modulation proceeds and the forward voltage will be lowered to the steady-state value. It is wellknown that the so-called “effective lifetime” τ_{eff} as a function of excess charge carrier concentration Δn (cm^{-3}) is considered as a practical concept for optimum operation of all electronic devices and integrated circuits; and the carrier lifetime larger or smaller is fully dependent on the carrier generation-recombination mechanisms [1-6].

The present work will concentrate on the evaluation of carrier lifetmes based on an earliar work by [7]. It will be shown that the conductivity modulation (conductivity changes) measurement can lead to the determination of carrier lifetime. This parameter is a very important and for further fabrication processes as for many electronic devices such as solar cells, sensors, nuclear detectors, switches and other bipolar or opto-devices. For instance, a silicon waveguide integrated with a lateral p-i-n optical diode was recently developed to form a phase modulator and tested with a simple technique related to lifetime measurement [8]. The other benfit of the current research work lies within the improvemnt of the computarized in-line carrier lifetime systems, such as the microwave relaxometers and wafer lifetime testers [9].

II. METHOD OF ANALYSIS

There are two well-known methods for determining the carrier lifetime known as the “Transient Technique” and the “Steady-State Method”. The first one is intended

---

Manuscript received Oct. 7, 2008; revised Nov. 28, 2008.

Renewable Energy & Environment Group, Department of Physics & Astronomy, College of Science, King Saud University, PO Box 2455, Riyadh 11451, Kingdom of Saudi Arabia
Tel: 00966-1-4676375, Fax: 00966-1-4673656
E-mail : uaelani@ksu.edu.sa

to measure τ_{eff} by injecting the silicon wafer/sample with excess charge carriers from typical external excitation sources such as electric field, optical pulses, gamma radiation and others [10-16]. Such sources will generate excess carriers and then the effective lifetime could be determined easily from the ratio dn/dt, where n is the minority carrier concentration cm^{-3} and t is the time (μs). The second way is known as the steady-state technique which requires only a fixed value of carrier generation. For simplicity, the carrier lifetime in the bulk region, p-type, silicon wafers can be determined from [10]:

$$\frac{\partial(\Delta n)}{\partial t} = G - U + \frac{1}{q}\nabla J \qquad (1)$$

where G is the generation rate $cm^{-3}.s^{-1}$, U is the net recombination rate in the bulk region ($cm^{-3}.s^{-1}$), q is the electronic charge, ∇ is a differential operator; and J is the electron current density (mA/cm^2). If surface effects are neglected and a uniform photogeneration is assumed, then Equation (1) is reduced to the determination of bulk carrier lifetime:

$$\tau_b = \frac{\Delta n}{U} \qquad (2)$$

Now, assuming σ_D is the dark conductivity given by:

$$\sigma_D = \frac{I}{2\pi\ .d.V} \qquad (3)$$

where, I is the injected current (A), V is voltage developed across the sample/wafer; and d is the inner spacing between probes (cm), (e.g the conventional In-Line Four Probes Technique, ILFP). If σ_γ is the conductivity due to gamma radiation, then the difference in conductivity is defined (the conductivity modulation $\Delta\sigma$) as:

$$\Delta\sigma = \sigma_\gamma - \sigma_D \qquad (4)$$

A similar expression to Equation (4) was developed previously by [18]:

$$\Delta\sigma_{ph} = \sigma_{ph} - B.\sigma_{ph} \qquad (5)$$

where, σ_{ph} is the photo-conductivity due to photon absorption, B is a constant related to temperature effects, e.g. B = 0.5 T; and T is the absolute temperature. On the other hand, the theoretical expression for $\Delta\sigma_{ph}$ can also be determined as follows [19]:

$$\Delta\sigma_{ph} = q.\Delta n.(\mu_n + \mu_p).W \qquad (6)$$

where, W is the sample/wafer thickness (μm) and μ_n, μ_p are the carrier mobilities for electron and hole respectively. Another analytical expression in photoconductive mechanism related to surface recombination velocity is given by :

$$\Delta\sigma_{ph} = (\mu_n + \mu_p).J_{ph}.(\frac{W}{2\,V_s} + \frac{W^2}{12\,D_n}) \qquad (7)$$

where, J_{ph} is the photo-generated current density (mA/cm^2), V_s is the surface recombination velocity (cm/s), D_n is the diffusion coefficient for electrons (cm^2/s). If V_s equals to zero at the top surface of the sample and V_s = infinite at the rear surface, then $\Delta\sigma_{ph}$ will be reduced to:

$$\Delta\sigma_{ph} = (\mu_n + \mu_p).J_{ph}.(\frac{W^2}{3D_n}) \qquad (8)$$

Based on the previous discussion in ref. [7], the effective lifetime of minority carrier is then given by:

$$\tau_{eff} = \frac{\Delta\sigma}{J.(\mu_n + \mu_p)}.W \qquad (9)$$

The temperature effect is not included in the present analysis. However, this effect on resistivity was mentioned earlier in Equation (5). The lifetime determination is considered in this work only under dark and gamma conditions. It is possible to distinguish the lifetime level form its magnitude (pico-s, nano-s, μs, ms..) according to sample size and device/wafer application [20-29].

III. EXPERIMENTAL PROCEDURE AND RESULTS

1. Preparation of Samples

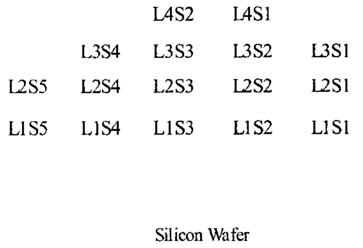
A number of monocrystalline silicon wafers is used throughout the present experimental work. Several wafers were taken from the same batch and are classified as wafer no. (Si#1), wafer no. (Si#2) etc. supplied by the High

Density Electronics Research Center (HiDEC) at Arkansas University, USA.

The silicon samples are then numbered horizontally and vertically across the surface of the wafers. For example, the symbol L3S4 means sample no. 4 line 3 (i.e. line zero starts from the diameter and up for each wafer and so on). A special mask was used with opening windows with an approximate area of 4 mm × 2 mm. A typical layout on each wafer is given in Fig. 1, a.

2. Measurements and Results

A schematic representation of the present experimenttal set-up is illustrated in Fig. 1, b. A computarised probe assembly was supplied by Jandel Engineering Ltd., UK, [30]. The sample geometry was controlled by the probes spacing. Current is passed through the outer two probee (P1-P4), and the potential developed across the two inner probes (P2-P3) is measured according to the in-line four-point probe ILFP technique. Then the dark conductivity σ_D is measured under dark conditions (no light or external excitation).



		L4S2	L4S1	
	L3S4	L3S3	L3S2	L3S1
L2S5	L2S4	L2S3	L2S2	L2S1
L1S5	L1S4	L1S3	L1S2	L1S1

Silicon Wafer

Fig. 1. a Typical geometrical distribution of planar test structures on silicon wafers, e.g. Si #1, Si #2, Si #3 etc. with a sample area of 4 mm × 2 mm.

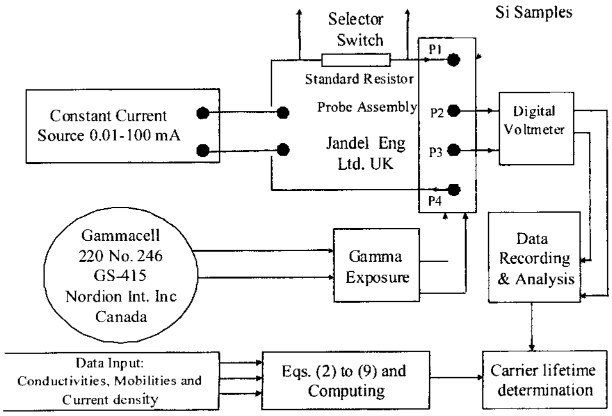


Fig. 1. b The experimental set-up for dark and gamma irradiation conductivities measurements at room temperature for carrier lifetime determination.

The induced change of gamma-conductivity σ_γ in silicon samples could be realised when samples are exposed to gamma rays. The used gamma source was a gamma cell 220 Model no. 246, with a Cobalt-60 source containing 24910 Curies (Nordion International Inc., Ontario, Canada). Only low intensity gamma radiation was considered with exposure times of 1 to 2 hours which is equivalent to nearly 6323 and 12647 Gy irradiation doses, respectively. The conductivity modulation values are then defined as the difference between gamma conductivity and dark conductivity according to Equations (3) & (4), and finally the effective lifetime was determined from Equation(9).

3. Dark, Gamma Conductivity and Conductivity Modulation

As earliar reported by Elani et al. [7], it was found that the dark conductivity σ_D increases at higher injected current levels and the average change in σ_D lies between 60 to 200 $\Omega^{-1}cm^{-1}$ acrorss the wafer no. Si#1, but σ_D was found to be less dependent on the injected current levels in the wafer no. Si#2. The uniformity of bulk resistivity could be an important factor for establishing the conductivity modulation mode. Exposing silicon wafers (n-type or p-type) to gamma radiation with different doses and time levels, showed an increase in their conductivity, and this may be attributed to the excess charge carriers produced by gamma irradiation; and this will lead to an improvement in the conductivities of nearly 2 to 3 times of their initial values. This result could be explained from the fact that the conductivity modulation causes a sharp increase in the gamma-induced conductivity σ_γ. Now the conductivity modulation can be deduced from Equation (4) and the sudden changes of $\Delta\sigma$ against the injected current makes maximum and minimum peaks through each run of conductivity measurement. Fig. 2 illustrates an example of $\Delta\sigma$ variation with the injected current. For instance, in sample no. L1S1 (e.g. Si#1) the maximum peak occurs at 225 $\Omega^{-1}cm^{-1}$ when the injected current was nearly 25 mA, whereas the minimum peak occurs at 160 $\Omega^{-1}cm^{-1}$, when

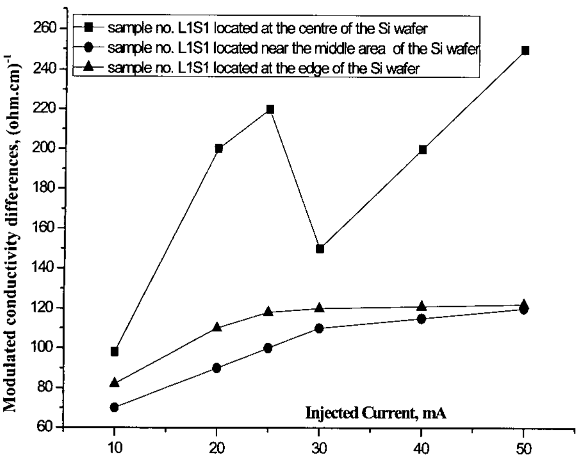


Fig. 2 Modulated conductivity variation with injected current in a silicon wafer for samples no. L1S1, L2S5 and L3S3 in the silicon wafer.

the current level was increased to 30 mA. This phenomena did not occur in samples located near the third line across the wafer, e.g. sample no. L2S5 (Si#1), and in this case $\Delta\sigma$ increases almost linearly. Now, for the samples located near the edges, $\Delta\sigma$ will be saturated at a current level above the level of 50 mA, e.g. sample no. L3S3 (Si#1). The change of $\Delta\sigma$ is therefore a very critical for selecting samples/wafers and must be considered for future fabrication procedures. Similar results were obtained in the other silicon wafers. Detailed information on such work could be found in [7].

4. Carrier Lifetimes Determination

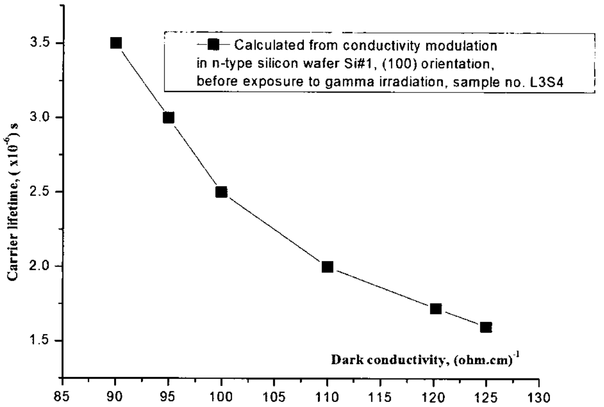


Fig. 3. Carrier lifetime variation with dark conductivity in wafer no. Si#1 before gamma irradiation.

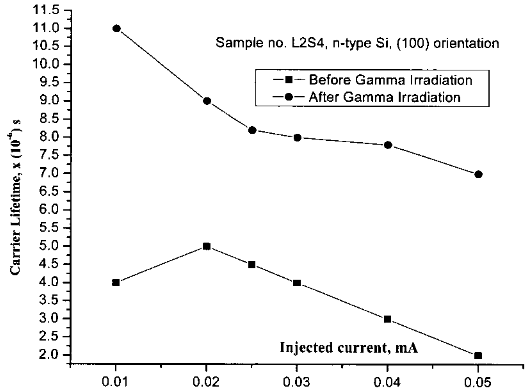


Fig. 4. Carrier lifetime variation with injected current in wafer no. Si#1.

Based on conductivity modulation measurements, the carrier lifetime was then determined using Equation (9) and the results were plotted against the dark conductivity as shown in Fig. 3 (e.g. sample no. L3S4). It is clear that the lifetime is decreased as the dark conductivity increased in this wafer Si#1 (n-type), and this could be explained from the fact that the wafers/samples must be kept at a low injection level in order to maintain higher lifetimes (i.e. in the case of photovoltaic devices). The same experiment was repeated on p-type Si#2 wafer, but in this case it is believed that p-type material will resist the gamma radiation more than n-type Si materials and thus the lifetime is expected at higher levels in these materials. This case could be applied for Si concentrated high-efficiency photovoltaic devices, space solar cells and substrate resistance modeling in Si devices/integrated circuits [31]. The effect of gamma radiation on carrier lifetimes is shown clearly in Fig. 4 (e.g. sample no. L2S4), where the carrier lifetime was improved in this sample from (2.5 μs to 4.5 μs) to about (7.5 μs to 11 μs), and this may reflect that the recombination rate was reduced to its minimum. Again similar results were obtained in other silicon wafers under consideration as shown in Figs. 5 & 6 respectively. Tables 1 & 2 show more additional results in several samples taken from different silicon wafers.

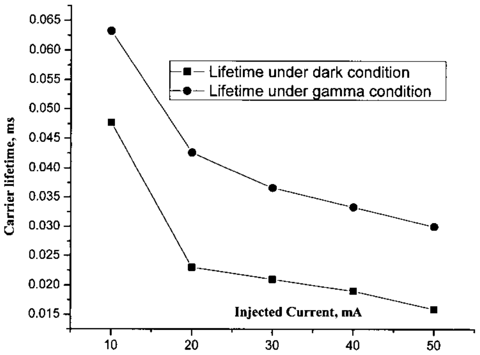


Fig. 5. Carrier lifetime variation with injected current in silicon wafer, sample L1S3.

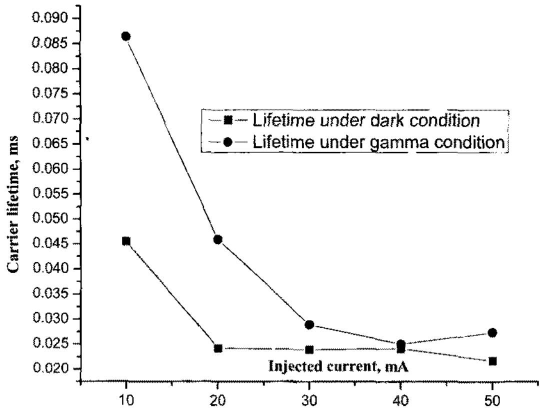


Fig. 6. Carrier lifetime variation with injected current in silicon wafer, sample L1S4.

Table 1. Carriers lifetime measurement based on conductivity modulation technique (dark and gamma irradiation lifetime measurements) for different silicon samples, L3S1, L3S2, L3S3 and L3S4, n-type, (100), Si wafers.

Sample no. L3S1

Injected current I , (mA)	Dark lifetime τ_D, (ms)	Gamma irradiation lifetime τ_γ, (ms)
10	0.0415	0.0539
20	0.0259	0.0314
30	0.0219	0.0264
40	0.0191	0.0226

Sample no. L3S2

Injected current I , (mA)	Dark lifetime τ_D, (ms)	Gamma irradiation lifetime τ_γ, (ms)
10	0.0477	0.0823
20	0.0298	0.0740
30	0.0300	0.0697
40	0.0290	0.0680
50	0.0227	0.0626

Sample no. L3S3

Injected current I , (mA)	Dark lifetime τ_D, (ms)	Gamma irradiation lifetime τ_γ, (ms)
10	0.0502	0.0764
20	0.0341	0.0659
30	0.0282	0.0616
40	0.0242	0.0557
50	0.0151	0.0477

Sample no. L3S4

Injected current I , (mA)	Dark lifetime τ_D, (ms)	Gamma irradiation lifetime τ_γ, (ms)
10	0.0455	0.0535
20	0.0265	0.0305
30	0.0228	0.0260
40	0.0199	0.0226
50	0.0147	0.0167

Table 2. Carriers lifetime measurement based on conductivity modulation technique (dark and gamma irradiation lifetime measurements) for different silicon samples, L4S1 and L4S2, n-type, (100), Si wafers.

Sample no. L4S1

Injected current I , (mA)	Dark lifetime τ_D, (ms)	Gamma irradiation lifetime τ_γ, (ms)
10	0.0531	0.0601
20	0.0273	0.0390
30	0.0235	0.0313
40	0.0202	0.0268
50	0.0134	0.0212

Sample no. L4S2

Injected current I , (mA)	Dark lifetime τ_D, (ms)	Gamma irradiation lifetime τ_γ, (ms)
10	0.0477	0.0780
20	0.0298	0.0606
30	0.0288	0.0562
40	0.0280	0.0325
50	0.0183	0.0262

IV. CONCLUSIONS

The conductivity modulation technique was introduced as a new approach for evaluating the minority carrier lifetime in silicon wafers/devices. The conductivity modulation mode was first measured after exposing the silicon samples to gamma irradiation. It was found that the conductivity level varies with injected currents between 25-30 mA. This mode is realized clearly at the central region of silicon wafers.

The carrier lifetime was determined from conductivity modulation mode, and was almost doubled after exposing the silicon wafers to low-level of gamma irradiation. Lifetime improvements were recorded as from 2.5 μs to 7.5 μs and from 4.5 μs to 11 μs respectively. Higher lifetimes in the n-type silicon substrates indicate that such materials could be operated under low injection level known for sensors, nuclear detectors and complex circuits IC's. Finally it is advised to adopt this method for evaluating other new semiconductors and nano-materials as well as for the development of a computerized unit to meet laboratory and industrial needs.

ACKNOWLEDGMENTS

The author would like to thank the Research Centre of

College of Science, King Saud University (KSU), Riyadh, Saudi Arabia for gamma measurement.

REFERENCES

[1] M. M., Moslehi, Semiconductor substrate minority carrier lifetime measurements, United States Patent No. 5,049,816, USA, 1991.

[2] A. W., Stephens, Application of photoconductance decay measurements to silicon solar cell characterisation, Ph.D Thesis, The University of New South Wales, Australia,1996.

[3] B. Carsten, The bipolar transistor is dead, longlive the bipolar transistor, http://www.powe-tech.com/Cartext.htm/, 15 pages, 2001.

[4] X. Y. Zhang, K. Banerjee, A. Ameraekera, V. Gupta, Z. Yu, and R. W. Dutton, Process and layout development substrate resistance modeling for deep sub-micron ESD protection devices, www.ee.Stanford.edu/~Kaustav/papers/IRS00-3pdf, 2001.

[5] A. R. Brwon, A. Asenov, J. R. Barker, P. Waind, and D. E. Crees, Calibration of the numerical simulations in the design of high temperature IGBT's, www.elec.gla.ac.uk/dev-mod/papers/isps94/isps.html, 6 pages, 2001.

[6] H. Nagel, C. Berge, and A. G.Aserle, Generalized analysis of quasi-steady-state and quasi-transient measurement of carrier lifetime in semiconductors, *J. Appl. Phys.*, 86, 11, 6218-6221, 1991.

[7] U. A. Elani, M. S. Al-Salhi, S. A. Kamh, and J. M. Al-Otaibi, The conductivity modulation of silicon samples under dark and gamma irradiation conditions, *Solar Energy*, 78, 23-29, 2005.

[8] D. W. Zheng, B. T. Smith, J. Dong, and M. Asghari, On the effective carrier lifetime of a silicon p-i-n diode optical modulator, *Semicond. Sci. & Technol.*, 23, (7pp), 2008.

[9] Telecom-STV, Telecom-STV Company Limited, Microwave Relaxometer Testing Equipment, www.telstv.ru, 2003.

[10] R. A. Sinton, Development of an in-line minority carrier lifetime monitoring tool for process control during fabrication of crystalline silicon solar cells, Annual Report, NREL/SR-520-35884, NREL National Renewable Energy Lab., Co, USA, 2004.

[11] S. M. Sze, Physics of semiconductor devices, 2nd Edition, Wiley, USA, 1981.

[12] J. A. Eikelboom, A. R. Burgers, Separation of bulk and surface recombination rates in silicon wafers using a new microwave reflections technique, *12th European Photovoltaic Solar Energy Conference*, Amersterdam, 1782-1783, 1994.

[13] A. Cuevas, R. A. Sinton, Prediction of the open-circuit voltage of solar cells from the steady-state photoconductance, Progress in Photovoltaics: Research & Applications; 5:79-90, 1997.

[14] K. L. Luke, L. J. Cheng, Analysis of the interaction of a laser pulse with a silicon wafer: Determination of bulk lifetime and surface recombination velocity, *J. Appl., Phys.*, 61, 6, 2282, 1987.

[15] M. DiGulio, S. Galassini, G. Micocci, A. Tepore, and C. Manfredotti, Determination of monority-carrier lifetime in silicon solar cells from laser-transient photovoltaic effect, *J. Appl. Phys.*, 52, 12, 7219-7223, 1981.

[16] K. Stewart, A. Cuevas, D. Macdonald, and J. Williams, Influence of copper on the carrier lifetime of n-type and p-type silicon, 11th Workdhop on Crystalline Silicon Solar Cell Materials and Processes, www.dspace.ann.edu.au, 4 pages, 2001.

[17] T. Maekawa, K. Fujiwara, and Y. Yamagishi, Contactless measurement of bulk carrier lifetime in thick silicon wafers by an induced eddy current, *Semicond. Sci. Technol.*, 10, 18-24, 1995.

[18] G. Yu, C. H. Lee, A. J. Heeger, N. Herron, and E. M. McCarron, Tansient photoinduced conductivity in single crystals of $YBa_2Cu_3O^{7-\delta}$:"photodoping" to the metallic state, *Phys. Rev. Letters*, 67(18): 2581-2584, 1991.

[19] A. Cuevas, M. Stocks, D. Macdonal, and R. Sinton, Applications of the quasi-steady-state photoconductance technique, *Proceedings of 2nd World Conf. And Exhibition on Photovoltaic Solar Energy Conversion*, Vol. 2, P.1236-1241, 1998.

[20] P. C. Taylor, Characterization of amorphous silicon advanced materials and PV devices, Final Technical Report, NREL/SR-520-38678, 39 pages, 2005.

[21] L. A. Zaroff, J. J. Brophy, Electronic properties in materials, Mc Graw-Hill, New York, USA., 1963.

[22] P. A. Barnes, Semiconductor characterization techniques, Prinetor Publication, 1978.

[23] S. C. Baber, Net and total shallow impurities

analysis of silicon by low temperature fourier transform infrared spectroscopy, *Thin Solid Films*, 72, 201-210, 1980.

[24] K. V. Ravi, Imperfections and impurities in semiconductor silicon, Jhon Wiley & Sons Inc, 184-200, 1981.

[25] F. Shimura, H. R. Huff, VLSI silicon material criteria, Academic Press, 191-269, 1985.

[26] N. K. Kishimoto, Radiation-resistant photoconductivity of doped silicon under 17 MeV proton bombardment, *J. Nuclear Materials*, 1244-1248, 1996.

[27] N. Kishimoto, H. Amekura, K. Kono, and C. G. Lee, Radiation resistance of amorphous silicon in optoelectric properties under proton bombardment, *J. Nucl. Mate.*, 1908-1913, 1998.

[28] A. Bentzen, H. Tathgar, A. Kopeak, R. Sinton, and A. Holt, Recombination lifetime and trap density variations in multicrystalline silicon wafers through the block, IEEE Publications, 1074-1077, 2005.

[29] Sinton Consulting, Inc., Silicon wafer lifetime tester, www.sintonconsulting.com, 2006.

[30] Jandel Engieneering Limited, Accuracy and Precision Probes and Test Equipement, www.jandel.co.uk., England, UK, 2001.

[31] M. Yamaguchi, S. J. Taylor, M. J. Yang., S. Matsuda, O. Kawasaki, and T. Hisamatsu, High-energy and high-fluence proton irradiation effects in silicon solar cells, *J. Appl. Phys.*, 80(9):4916-4920, 1996.

Ussama A. Elani received a B.Sc. degree in Physics and Chemistry in 1976, the M. Sc. degree in Mechanical Eng. (Selective solar materials), Birmingham University, UK, 1981, and a Ph.D. degree in Silicon Microelectronics, The University of Wales, Cardiff, UK, 1985.

He was a Scientific Researcher at King Abdulaziz City for Science & Technology, Energy Research Institute, Riyadh, Saudi Arabia between 1993-1997 in the field of energy information and renewable energy technologies.

He is now an Associate Professor in the Department of Physics & Astronomy at King Saud University, Riyadh, Saudi Arabia since 1998.

His current interests are Silicon and InP devices, nano-Ag material, energy education and the role of renewable energy policy with environmental issues at national and regional levels.