EXAMEN PENTRU ATESTAREA CONSILIERILOR

Brevete de invenţie

22.02.2007

Domeniul tehnic de specialitate: Electricitate

Proba practică 2:

Redactarea răspunsului la o notificare transmisă de O.S.I.M.

Sunteţi, în conformitate cu art. 41 din Legea nr. 64/1991, privind brevetele de invenţie, republicată, reprezentantul autorizat, în faţa OSIM, al unui solicitant care a înregistrat la OSIM o cerere de brevet de invenţie de invenţie nr. a 2002 0402 (fictiv), în vederea obţinerii protecţiei prin brevet pentru o invenţie cu titlul "Metodă şi instalaţie pentru controlul nedistructiv al structurilor semiconductoare".

Aveţi la dispoziţie următoarele:

1. Notificarea OSIM conţinând rezultatele examinării în fond a invenţiei revendicate din cererea de brevet privind îndeplinirea condiţiilor de brevetabilitate realizată pe baza analizei comparative cu materialele relevante selectate din stadiul cunoscut al tehnicii (**anexa I**- o filă);

2. O copie a descrierii invenţiei şi revendicărilor şi desenului aşa cum au fost depuse la OSIM de către solicitant (**anexa II**- 5 file);

3. Documente relevante selectate din stadiul tehnicii, consemnate în notificare, faţă de care s-a efectuat analiza comparativă. (**Anexa III**- 5 file)

✍ **Vi se cere:**

Redactaţi răspunsul la notificare (anexa I), exprimând punctul dv. de vedere faţă de observaţiile din notificare, prin argumentaţie tehnică bazată pe descrierea invenţiei şi revendicărilor, care să justifice îndeplinirea condiţiilor de brevetabilitate şi să reformulaţi dacă este cazul revendicările iniţiale, având în vedere observaţiile rezultate din examinarea de fond consemnate în notificarea OSIM.

ANEXA I

NOTIFICARE O.S.I.M.

Examinarea cererii de brevet de invenţie nr. a 2002 0402/14. 07. 2002,cu titlul "Metodă şi instalaţie pentru controlul nedistructiv al structurilor semiconductoare", comparativ cu stadiul cunoscut al tehnicii stabilit în cursul examinării şi în baza prevederilor legislaţiei de brevete a condus la următoarele constatări:

1. Invenţia se referă la o metodă şi instaţie pentru controlul nedistructiv al structurilor semiconductoare, caracteristice dispozitivelor semiconductoare.

2. Invenţia în raport cu conţinutul revendicării 1 şi a domeniului de aplicare precizat în descriere nu are noutate, regăsindu-se în documentul D1(brevetul US 4393348 cu titlul"Metodă şi aparat pentru determinarea lungimii de difuzie a purtătorilor minoritari în semiconductori" publicat la 12.07.1983) (anexat prezentei). D1 se referă la o metodă şi un aparat folosit pentru determinarea lungimii de difuzie a purtătorilor minoritari în semiconductori. D1 are acelaşi domeniu de aplicare ca şi invenţia revendicată şi anume controlul materialelor semiconductoare. Metoda se bazează pe iluminarea probei, excitarea purtătorilor minoritari care produc o tensiune fotovoltaică la suprafaţa preluată de un detector şi transmisă unui sistem electronic de prelucrare. Aparatul cuprinde o sursă de lumină monocromatică, un sistem de focalizare, un monocromator, un detector, un ansamblu de electrozi şi un circuit electronic (comparator, compensator, înregistrator, etc). Metoda se bazează în principiu pe aceleaşi etape principale ca cele din invenţia revendicată în revendicarea 1 şi anume iluminarea structurii supusă testării cu radiaţie luminoasă acordabilă, generarea radiaţiei de fotoluminiscenţă de către purtătorii de sarcină excitaţi. Prin urmare revendicarea 1 referitoare la metodă, în forma actuală nu se poate admite.

3. Având în vedere că invenţia în forma actuală nu este nouă considerăm că revendicarea 1, respectiv metoda de control nedistructiv nu îndeplineşte cerinţele art. 7,

8 din Legea nr. 64/1991 republicată prin legea 203 şi în consecinţă- brevetul de invenţie solicitat nu poate fi acordat. Dacă consideraţi că invenţia dv. are elemente de nouate faţă de brevetul menţionat vă rugăm să refaceţi revendicarea 1 referitoare la metodă, punând în evidenţă stadiul tehnicii.

Faţă de cele prezentate anterior vă rugăm să ne comunicaţi eventualele dvs. observaţii, inclusiv eventualele revendicări reformulate, în termen de maximum 60 de zile de la data expedierii prezentei, cunoscând că, ulterior, cererea dvs. de brevet va fi prezentată comisiei de examinare, în vederea luării unei hotărâri, exclusiv pe baza documentelor existente la dosar.

ANEXA I I

Metodă şi instalaţie pentru controlul nedistructiv al structurilor semiconductoare

Invenţia se referă la o metodă şi instalaţie pentru controlul nedistructiv al structurilor semiconductoare, caracteristice dispozitivelor semiconductoare, obţinute în urma diferitelor procese tehnologice, cum ar fi epitaxia, predifuzia, implantarea ionică, tratament termic etc.

Sunt mai multe metode pentru controlul nedistructiv al materialelor semiconductoare care folosesc fie măsurarea timpului de viaţă al purtătorilor de sarcină în semiconductor, analiza spectrelor de absorbţie, fotoluminiscenţă sau excitaţie de fotoluminiscenţă. Toate aceste metode constau în principal in excitarea purtătorilor de sarcină din materialul semiconductor cu ajutorul unor impulsuri de lumină generată de surse incoerente sau surse laser şi din analiza în domeniul timp sau în domeniul frecvenţă a radiaţiei de fluorescenţă emise de materialul semiconductor.

Instalaţiile construite pe baza acestor metode sunt constituite in general dintr-o sursă de lumină, un sistem de focalizare a luminii pe materialul de controlat, un sistem de detecţie (monocromator-detector) şi un spectroscop.

Aceste metode şi instalaţii prezintă însă o serie de dezavantaje şi anume:

- nu pot fi folosite pentru zone mici datorită difuziei purtătorilor
- datorită limitării spectroscoapelor existente, dispozitivele optice folosite acceptă lumina emisă dintr-o regiune mult mai mare decât zonele caracteristice dispozitivelor semiconductoare.

Problema pe care o rezolvă invenţia constă în controlul regiunilor microscopice pentru rezolvarea spaţială (de adâncime şi de suprafaţă) a spectrelor de fotoluminescenţă în cazul excitării energetice cu radiaţie laser a probelor semiconductoare.

Metoda pentru controlul nedistructiv al structurilor semiconductoare conform invenţiei rezolvă problema de mai sus prin aceea că prevede filtrarea spaţială a radiaţiei de fotoluminiscenţă prin preluarea ei doar dintr-o zonă restrînsă de dimensiuni microscopice corespunzătoare focarului unui obiectiv de microscop şi înlăturarea luminii generate în toate punctele cele situate pe axul optiec ca şi în cele situate pe axul optic dar diferite de focarul menţionat focalizarea radiaţiei obţinute detecţia şi analiza spectrală a acestei radiaţii.

Instalaţia pentru controlul nedistructiv al structurilor semiconductoare conform metodei este constituită dintr-un laser acordabil care transmite radiaţia luminoasă prin două fante pe o oglindă ce o dirijează printr-o altă fantă şi un obiectiv de miscroscop pe structura semiconductoare în care excită purtătorii de sarcină, radiaţia de fluorescentă produsă de aceştia fiind transmisă prin două ecrane absorbante pe un ai doilea obiectiv de microscop în focarul căruia este concentrată, focar situat într-o fantă circulară microscopică practicată în cel de-al treilea ecran care elimină lumină generată în toate punctele situate pe axul optic, lumina obţinută fiind focalizată pe fanta unui monocromator detectată de un detector, iar spectrul ei prelucrat cu un calculator.

Metoda şi instalaţia pentru controlul nedistructiv al structurilor semiconductoare, conform invenţiei prezintă următoarele avantaje:

- permite optimizarea tehnologiei de fabricaţie a componentelor electronice;

- permite controlul regiunilor microscopice caracteristice dispozitivelor semiconductoare;

- permite identificarea şi determinarea cantitativă a unei game largi de defecte care introduc nivele de energie în apropierea marginilor benzilor de conducţie şi de valenţă cum ar fi impurităţi ca da exemplu: P, B, As, Al, Ca, Bi, In, Tl, Li, Se, Mg, etc. măsurarea degradării reţelei cristaline introduse de diferite procese ca de exemplu implantarea ionică şi chiar tensiuni mecanice în reţeua cristalină;

- conduce la creşterea randamentului de fabricaţie ale componentelor electronice.

Se dă, în continuare un exemplu de realizare a invenţiei, în legătură şi cu figura care reprezintă schema bloc principială a instalaţiei.

Metoda pentru controlul nedistructiv al structurilor semiconductoare constă în luminarea structurii cu radiaţie luminoasă acordabilă, generarea radiaţiei de fotoluminiscenţă de către purtătorii de sarcină ce au fost excitaţi, filtrarea spaţială a radiaţiei de fotoluminiscenţă prin alegerea unei zone restrânse de dimensiuni microscopice corespunzătoare focarului unui obiectiv de microscop pentru preluarea radiaţiei de fotoluminiscenţă şi înlăturarea luminii generate în toate punctele nesituate pe axul optic ca şi în cele situate pe axul optic, dar diferite de focarul menţionat, focalizarea radiaţiei obţinute detecţia şi analiza spectrală a acestei radiaţii.

Instalaţia conform invenţiei şi în legătură cu figura este alcătuită dintr-un laser acordabil **1** care transmite radiaţia luminoasă prin două fante **2** şi **3** pe o oglindă **4** ce o dirijează printr-o fantă şi un obiectiv de microscop **6** pe proba semiconductoare în care excită purtători de sarcină. Obiectivul de microscop **6** preia radiaţia de fotoluminiscenţă din focarul **0** şi o trimite sub formă de raze paralele printre două coroane absorbante **8** şi **9** pe un obiectiv de microscop **10** care concentrează această lumină în focarul său $\mathbf{O_1}$ aflat într-o fantă circulară a upui ecran absorbant **11** care are rolul să elimine din sistem lumina generată în afara axului optic. Lumina generată pe axul optic între, focarul **O** şi obiectiv va fi absorbită de ecranul cilindric exterior **8**, (exemplu razele B-B_1), iar lumina generată pe axul optic între focarul **O** şi planul de la infinit va fi absorbită pe ecranul interior **9** (exemplu razele A-A_1; A-A_1).

Imaginea $\mathbf{O_1}$ a focarului **O** este refocalizată de un obiectiv de microscop **12** pe o fantă **13** a unui monocromator 14, după care radiaţia este detectată de un detector **15**, iar spectrul este prelucrat cu un sistem electronic cu calculator **16** care realizează şi sincronizarea sistemului de prelucrare a canalului purtător de informaţie şi a laserului cu scopul eliminării radiaţiei difuzate provenind de la laserul de excitaţia.

Rezoluţia superficială a sistemului este dată de dimensiunea fantei circulare a ecranului **11**, iar rezoluţia de adâncime este dată da expresia:

$$x = f \frac{\alpha}{R} \frac{R-r}{L}$$

unde f este distanţa focală a obiectivului de microscop, R-raza ecranului cilindric exterior,

r-raza ecranului cilindric interior şi L-lungimea celor două ecrane cilindrice.

Revendicări

1. Metodă pentru controlul nedistructiv al structurilor seminconductoare **caracterizată prin aceea că** cuprinde luminarea structurii supusă testării cu radiaţie luminoasă acordabilă, generarea radiaţiei de fotoluminiscenţă de către purtătorii de sarcină excitaţi, filtrarea spaţială a radiaţiei de fotoluminiscenţă prin preluarea ei doar dintr-o zonă restrânsă de dimensiuni microscopice, corespunzătoare focarului unui obiectiv de microscop şi înlăturarea luminii generate în toate punctele nesituate pe axul optic ca şi în cele situate pe axul optic dar diferite de focarul menţionat, focalizarea radiaţiei obţinute, detecţia şi analiza spectrală a acestei radiaţii.

2. Instalaţie pentru controlul nedistructiv al structurilor semiconductoare conform metodei de la revendicarea 1, **caracterizată prin aceea că** este constituită dintr-un laser acordabil (**1**) care transmite radiaţia luminoasă prin două fante (**2, 3**) pe o oglindă (**4**), ce o dirijează printr-o altă fantă şi un obiectiv de microscop (**6**) pe structura semiconductoare (**7**) în care excită purtătorii de sarcină, radiaţia de fluorescentă produsă de aceştia fiind transmisă prin două ecrane absorbante (**8, 9**) pe un al doilea obiectiv de microscop (**10**) în focarul căruia este concentrată, focar situat într-o fantă circulară microscopică practicată în cel de-al treilea ecran (**11**), care elimină lumina generată în toate punctele nesituate pe axul optic, lumina obţinută fiind focalizată pe fanta unui monocromator (**14**), detectată de un detector (**15**), iar spectrul este prelucrat cu un calculator (**16**).

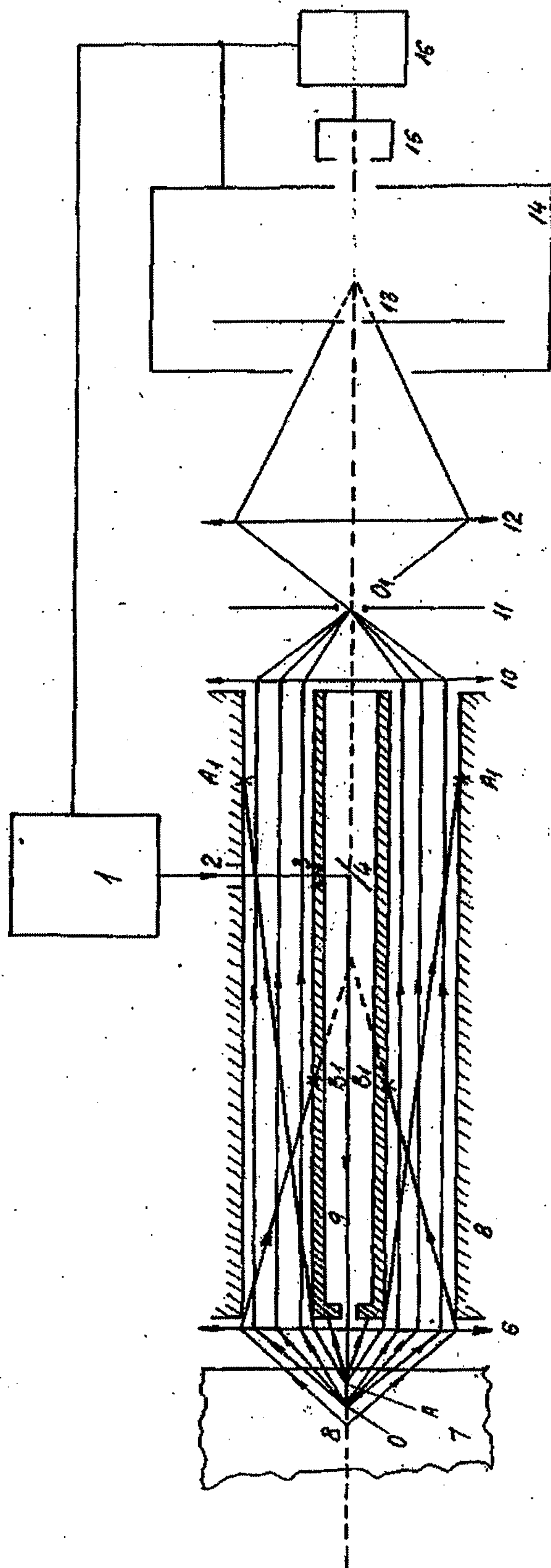

Fig. 1

United States Patent [19]

Goldstein et al.

[11] **4,393,348**

[45] **Jul. 12, 1983**

[54] **METHOD AND APPARATUS FOR DETERMINING MINORITY CARRIER DIFFUSION LENGTH IN SEMICONDUCTORS**

[75] Inventors: **Bernard Goldstein; Joseph Dresner,** both of Princeton; **Daniel J. Szostak,** Mercerville, all of N.J.

[73] Assignee: **RCA Corporation,** New York, N.Y.

[21] Appl. No.: **228,575**

[22] Filed: **Jan. 26, 1981**

[51] **Int. Cl.**3 .... **G01R 31/26**
[52] **U.S. Cl.** .... **324/158 R;** 324/158 D
[58] **Field of Search** .... 324/158 R, 158 D, 158 T, 324/73 R

[56] **References Cited**

U.S. PATENT DOCUMENTS

4,333,051 6/1982 Goodman .... 324/158 R

OTHER PUBLICATIONS

Ashcroft, N. W. et al.; Solid State Physics; Holt, Rinehart and Winston; New York; 1976; pp. 360–362.

Primary Examiner—Ernest F. Karlsen

Attorney, Agent, or Firm—Birgit E. Morris; Donald S. Cohen; Joseph D. Lazar

[57] ABSTRACT

Method and apparatus are provided for determining the diffusion length of minority carriers in semiconductor material, particularly amorphous silicon which has a significantly small minority carrier diffusion length using the constant-magnitude surface-photovoltage (SPV) method. An unmodulated illumination provides the light excitation on the surface of the material to generate the SPV. A manually controlled or automatic servo system maintains a constant predetermined value of the SPV. A vibrating Kelvin method-type probe electrode couples the SPV to a measurement system. The operating optical wavelength of an adjustable monochromator to compensate for the wavelength dependent sensitivity of a photodetector is selected to measure the illumination intensity (photon flux) on the silicon. Measurements of the relative photon flux for a plurality of wavelengths are plotted against the reciprocal of the optical absorption coefficient of the material. A linear plot of the data points is extrapolated to zero intensity. The negative intercept value on the reciprocal optical coefficient axis of the extrapolated linear plot is the diffusion length of the minority carriers.

13 Claims, 5 Drawing Figures

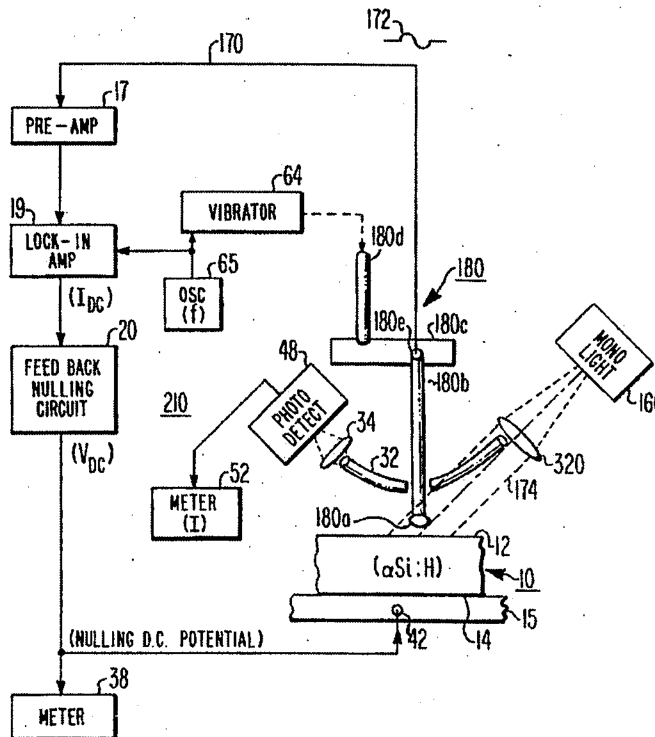

Fig. 1

Fig. 2

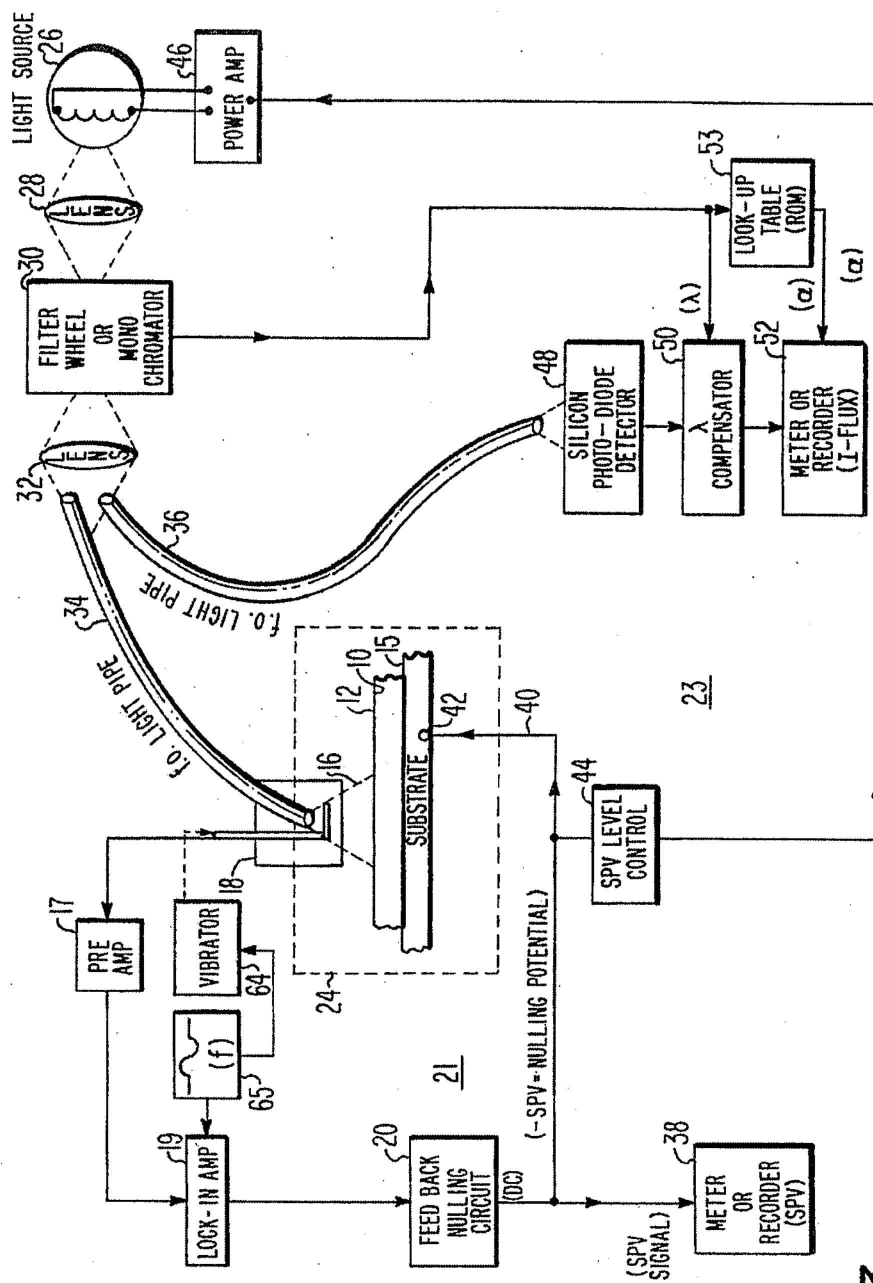

Fig. 3

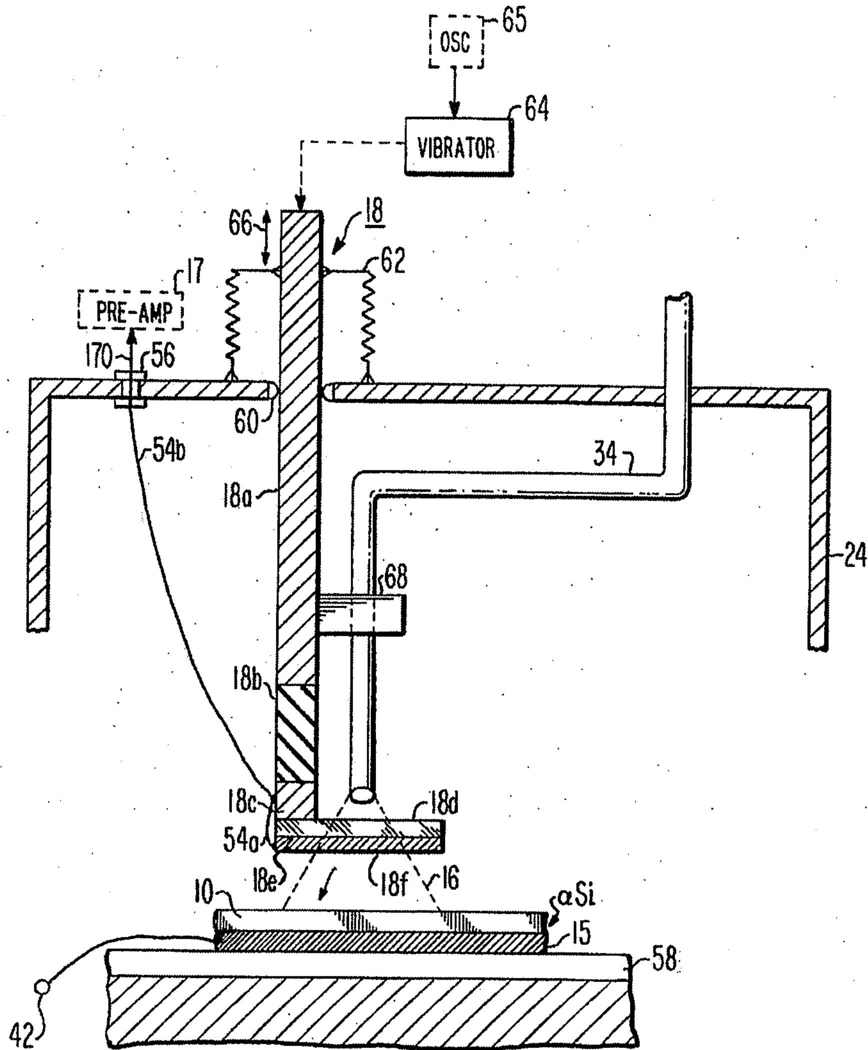

Fig. 4

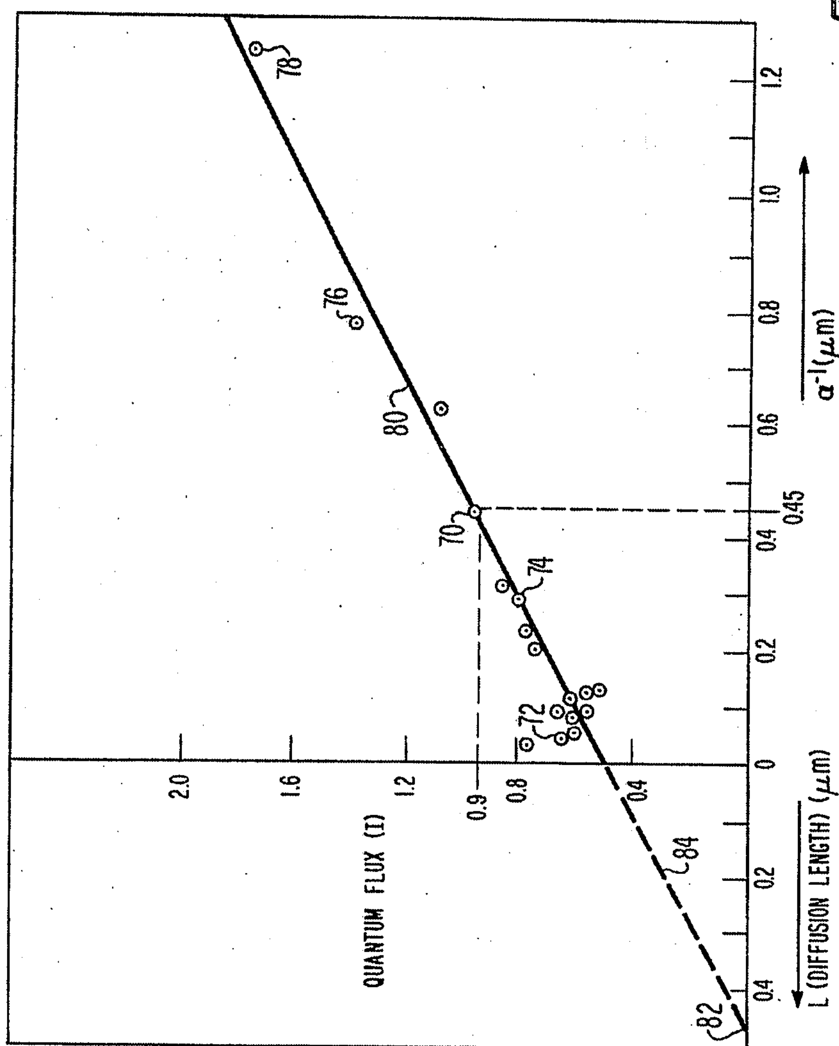

Fig. 5

METHOD AND APPARATUS FOR DETERMINING MINORITY CARRIER DIFFUSION LENGTH IN SEMICONDUCTORS

BACKGROUND OF THE INVENTION

The Government of the United States of America has rights in this invention pursuant to Subcontract No. XJ-9-8254-1 awarded by the Department of Energy.

This invention relates to an apparatus for determining the minority carrier diffusion length in semiconductors using the constant-magnitude surface-photovoltage (SPV) method.

Apparatus and methods for determining the minority carrier diffusion length (L) using the SPV method are well known. In brief, the principle of the diffusion length (L) determination requires the illumination of a specimen surface with monochromatic radiation of energy slightly greater than the bandgap of the semiconductor. Electron-hole pairs are produced and diffuse to the illuminated (front) surface where they are separated by the electric field of the depletion region (i.e., the surface-space-charge region) to produce a surface photovoltage (SPV). A portion of the SPV signal is coupled to an amplifier for amplification and measurement. The photon intensity (photons per second) is adjusted to produce the same magnitude of SPV at various wavelengths of illumination. The photon intensity required to produce this constant magnitude SPV signal is conveniently plotted on the ordinate against the reciprocal of the absorption coefficient on the abscissa for each wavelength. The resultant plot is linear and is extrapolated to the zero intensity intercept on the negative abscissa. This intercept value is the effective diffusion length (L). For a more detailed description of the theory and background for this method, see an article "A Method for the Measurement of Short Minority Carrier Diffusion Lengths in Semiconductors," by A. M. Goodman in the *Journal of Applied Physics,* Vol. 32, No. 12, pp. 2550–2552, December 1961. The American Society for Testing and Materials has adopted a standard using this method which is published as ASTM F 291-78. The ASTM standard, when implemented according to the block diagram of FIG. 1 of ASTM F 291-78, is provided particularly for testing the diffusion length (L) for minority carriers in silicon but the method in general may be used for other semiconductor materials.

See U.S. patent application, entitled "Method and Apparatus for Determining Minority Carrier Diffusion Length in Semiconductors", Ser. No. 153,920, filed on May 28, 1980 by A. M. Goodman now U.S. Pat. No. 4,333,501, issued June 1, 1972, for a description of an apparatus using this principle in which a servo system maintains a constant predetermined value of the SPV, thereby allowing the measurements to be carried out in a relatively short time. This minimizes the effects of drift caused by laterially diffusing minority carriers during a test. Moreover, this Goodman application describes a capacitance-pickup electrode which is placed to make physical contact with the surface of a semiconductor material to sense SPV test signals. The SPV method uses a surface junction to effect what may be termed "band-bending" to collect minority carriers generated at various depths by monochromatic light of varying absorption coefficient. In such SPV methods, as described in the Goodman patent application, the exciting light is chopped or modulated in order to develop a.c. components of the SPV pickup or detection by a capacitance pickup or probe. The Goodman method however is not suitable for measuring the significantly small diffusion length of amorphous silicon which is known to exhibit very slow transients in SPV generated by chopped or modulated light.

Another conventional method for measuring the minority carrier diffusion length (L) of semiconductor material involves measuring a certain distance on the semiconductor which distance is on the order of the length L. See J. N. Shive, "Properties, Physics and Design of Semiconductor Devices," Van Nostrand, N.Y. 1959, p. 337, for a description of this method. This measurement is very difficult to use for amorphous silicon because L is about or less than a few thousand angstroms, i.e. 2–3 μm.

SUMMARY OF THE INVENTION

According to the present invention, the diffusion length (L) of minority carriers of amorphous silicon is determined by illuminating the surface of the silicon with steady (d.c.) light and measuring the surface potential (SPV) with a non-contacting vibrating Kelvin probe.

BRIEF DESCRIPTION OF THE DRAWING

In the drawing:

FIG. 1 is a schematic illustrating the geometric parameters of a semiconductor specimen useful in understanding and practicing the invention;

FIG. 2 is a simplified schematic of the elements in general used in practicing the measurement method of the invention;

FIG. 3 is a block schematic of the preferred form of apparatus useful in practicing the invention;

FIG. 4 is a schematic in fragmentary form of a portion of the apparatus of FIG. 3; and

FIG. 5 is a plot of the quantum flux I versus the reciprocal of the absorption coefficient.

DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT

The measuring apparatus of the invention as illustrated in FIG. 2, to be described, provides a means using a modified version of the constant-magnitude surface photovoltage (SPV) method for determining the minority carrier diffusion length (L) in a semiconductor formed of the type that will be defined. In the embodiment to be described, the wafer for which the diffusion length is to be measured is a layer of hydrogenated amorphous silicon (αSi:H). Nevertheless, the invention, it is to be understood, can be used to determine the diffusion length of minority carriers in semiconductor materials other than those in which the diffusion length is significantly small, provided the thickness of the semiconductor material wafer being tested is at least greater than the diffusion length of the minority carrier and preferably four times that diffusion length. Such semiconductor material includes, but is not necessarily limited to, silicon, germanium, gallium arsenide indium phosphide as well as amorphous semiconductor material.

The geometry of a specimen wafer **10** is illustrated in FIG. 1. Wafer **10** is assumed to be in the form of a semiconductor slab having a thickness l formed in the embodiments to be described of hydrogenated amorphous silicon. One surface **12** is uniformly illuminated

by a steady d.c. monochromatic light **16** from a source of photon energy hu, slightly greater than the band gap (E_G) of the semiconductor material, while the opposite surface **14** is kept dark. The flux of the light quanta is represented by I in relative units. Electron hole pairs are produced by the absorbed photons. Some of these pairs diffuse to the illuminated surface **12** where they are separated by the electric field of the depletion or surface-space-charge region **13** having a thickness l_1, producing a surface photovoltage (SPV).

The SPV is capacitively coupled to a Kelvin method-type probe **180** shown in FIG. **2** adjacent to the illuminated face **12**. The probe **180**, when vibrated, serves to couple capacitively an electrical signal derived from the field at the surface **12** to the measuring apparatus. Probe **180** embodies the well known Kelvin principle for sensing surface potentials. See Solid State Physics by Ashcroft et al., Holt, Rinehart and Winston, (1976), pp. 360–362, for an illustration of the use of the Kelvin method. Any suitable probe for deriving a voltage representing the SPV may be used in the practice of this invention. The probe **180** shown in FIG. **2** is a laboratory form while the probe **18** shown in FIGS. **3** and **4** to be described shows a form of the probe useful for manufacturing or production facilities.

Probe **180** is formed of a ball **180*a*** formed of gold about 2 mm in diameter, attached to a stainless steel screw **180*b*** about 1 cm long. An insulator **180*c*** formed of plastic or glass is connected to a steel rod **180*d*** and carries screw **180*b***. A terminal **180*e*** is connected to a conductor **170** for connecting electrical signals to a preamplifier **17**.

Probe **180** is vibrated vertically along its axis by a vibrator **64** of suitable form such as a torque motor. The vibrator is driven at a fixed frequency (f) by an oscillator **65**. The frequency f is within the range of 10–10,000 Hz. In the embodiments being described f is 640 Hz. Probe **180** is spaced about 1–4 mm over surface **12** and is vibrated with an amplitude of about 0.5 mm. Moreover, the beam **174** should illuminate the surface **12** via lens **320**, for example, over a substantial area greater than the projected area of the probe ball **180*a*** to reduce illumination edge effects. A voltage signal **172**, having a frequency f with a magnitude on the order of 100–200 millivolts, is developed by the probe **180** when vibrated at frequency f and is applied via path **170** to the preamplifier **17**. This voltage **172** represents the SPV of wafer **10**, after illumination, in ac form.

Amplified voltage **172** is then applied to a lock-in amplifier **19** which provides a d.c. current output serving as an error signal to a feedback potential nulling circuit **20**. Lock-in amplifier **19** is operated by a signal at a frequency f from source **65**. Source **65** may provide a signal at a selected frequency within the range of 10–10,000 Hz. Accordingly, amplifier **19** is phase and frequency locked to voltage **172**. Feedback circuit **20** functions to null the error signal with a nulling potential equal to the d.c. SPV potential of the illuminated wafer **10**. Circuit **20** is a suitable operational amplifier arranged to provide a d.c. potential output in response to the d.c. current input from lock-in amplifier **19**. This potential is applied to terminal **42** of conductive substrate **15** and thus to the bottom surface **14** of wafer **10**. The nulling potential tends to reduce the error signal towards zero. The magnitude of the nulling potential can be measured by a meter **38**. The measured potential is equal and opposite to the SPV.

The intensity of light source **160** should be sufficient to develop an appreciable SPV on surface **12** and yet not be so great as to saturate the bending of the energy bands. For amorphous silicon, band bending saturation occurs for SPV values at about 300 millivolts.

A portion of the light from the source **160** is used to provide an indication of the quantum of flux (I) illuminating the surface **12** via a light pipe **32** suitably positioned in the light beam **174**. Light can be, in the alternative, sampled by positioning a half-silvered mirror in the beam **174** to pass a portion of the light to the surface **12** and reflect a portion of the light to a detector, such as a photodiode detector **48**. Photodetector **48**, responsive to the sampled light via light pipe **32** and lens **34**, provides such an indication as measured by I-meter **52**. Suitable calibration of the flux I reading is needed to compensate for the wavelength dependent response of the detector **48** for each different wavelength of light source **160** used for the measurements. In practicing the invention in the laboratory, the wavelength compensation is done by calculation. In practical application apparatus is provided to automatically compensate for wavelengths as illustrated in FIG. **3** to be described.

As explained in greater detail in the above patent application of A. M. Goodman, the value of the surface photovoltage (SPV) is used to determine the diffusion length L at a given wavelength of light.

The magnitude of the SPV depends on both the optical absorption coefficient $\alpha(cm^{-1})$ and the photon flux I (photons $-cm^{-2}$-sec^{-1}). A series of different wavelength (λ) values is selected to give different values of the absorption coefficient. At each value of the wavelength λ, the flux I is adjusted to give the same value of the SPV, that is, a constant magnitude of the SPV. If I is plotted against the reciprocal of the absorption coefficient (α^{-1}) for each of these constant magnitude SPV points, the result is a linear graph whose extrapolated intercept on the negative reciprocal absorption coefficient axis is the effective diffusion length (L). An example of such a graph is illustrated in FIG. **5** to be described further hereinafter. The thickness of the material l must be much greater than the diffusion length L. In practice, a material thickness (l) of at least four times the diffusion length (L) is preferred although the invention provides practical measurements for material of thicknesses between two and four times L.

In the operation of the apparatus shown in FIG. **2**, light from source **160** at a first predetermined wavelength illuminates surface **12** while vibrator **64** causes probe **180** to be oscillated or vibrated along its vertical axis over the surface **12**. The alternating voltage signal **172** is derived from the SPV developed by the light. The signal **172** is coupled to preamplifier **17**, providing an amplified version of signal **172** which in turn is applied to lock-in amplifier **19** serving essentially as a synchronous detector which is gated by an oscillating signal at frequency f from oscillator **65**. The signal from oscillator **65** also actuates vibrator **64** for oscillating the probe **180**. Accordingly, the probe **180** and the lock-in amplifier **19** are frequency and phase locked. Amplifier **19** provides a d.c. current representing the magnitude of the derived SPV voltage **172**. This serves as the error signal of a feedback loop **210** formed of the probe **180**, pre-amp **17**, amplifier **19**, and nulling circuit **20**. The error signal from amplifier **19** is applied to the feedback nulling circuit **20** which provides a voltage potential proportional to the error input signal. Nulling circuit **20** is suitably an operational amplifier having a high input

impedance and a low output impedance for coupling a nulling potential to the substrate **15**. The output signal of circuit **20** is a nulling d.c. potential which, when applied to terminal **42** of substrate **15**, tends to oppose the SPV potential developed in the wafer **10**. When the magnitude of the nulling d.c. potential applied to terminal **42** is equal and opposite to the SPV, the loop **210** will have reduced the error signal from amplifier **19** to zero. The meter **38** indicates the magnitude of this nulling potential which is equal to the magnitude of the SPV.

A series of tests at different wavelengths of light source **160** are performed in a similar manner. Thus, a second wavelength is selected for light source **160** to illuminate the surface **12**. The circuit operates to provide a reading of meter **38** indicative of the SPV. In order to make the series of tests complying with the constant SPV requirement explained above, the intensity of light source **160** for each wavelength is adjusted until the meter **38** displays a magnitude of the nulling potential that is equal to the SPV value of the first measurement at the first selected wavelength. A series of such illumination steps at different wavelengths are repeated to provide a fair number of sample points of the type indicated by points **72, 74, 76** and **78** illustrated in FIG. 5. Each sample point is referenced to FIG. 5 by the quantum flux (I) needed to develop the constant SPV value. This flux value is determined by meter **52** providing a display of the sampled light detected by photodetector **48**.

For each point to be plotted as illustrated by FIG. 5, the absorption coefficient α is determined from the respective wavelengths of light used for each test point. These points are then plotted as shown in FIG. 5. For example, for point **70** for a quantum flux I of 0.9, the absorption coefficient for the wavelength of the light is approximately 0.45. A plurality of such test points are plotted and a line **80** is drawn as indicated to extend into the negative axis which, as known, and explained above represents the diffusion length L in micrometers. In the example illustrated, the intersection point **82** indicates a diffusion length L equal to 0.41 micrometers for the particular specimen of amorphous silicon tested.

While the apparatus illustrated in FIG. 2 is suitable to practice the invention in laboratory or limited manufacturing operations, it is desirable that the apparatus be arranged for manufacturing use. Such an apparatus is illustrated in FIG. 3. The feedback loop **21** portion of FIG. 3 is essentially the same as feedback loop portion **210** of FIG. 2. The apparatus of FIG. 3 provides for a different form of probe to use light via fiber optics. Moreover, FIG. 3 provides for automatic feedback means to adjust the light intensity to maintain the SPV constant as well as an automatic feedback means to null the error signal. An enlarged more detailed portion of FIG. 3 illustrating the surface voltage sensing means is illustrated in FIG. 4.

A beam of polychromatic light from a source of light **26** is passed through a first lens **28**, a filter wheel or monochromator **30** and a second lens **32** to a first fiber optic light pipe **34** and a second fiber optic light pipe **36**. The monochromatic light from pipe **34** provides the illuminating light **16** applied to the surface **12** of the sample **10** mounted on substrate **15**. Another Kelvin method-type probe **18**, shown in greater detail in FIG. 4 to be described, responding to the surface voltage generated at the surface **12** of the sample **10** provides a voltage input first to a pre-amplifier **17** and then to lock-in amplifier **19**. Amplifier **19** is coupled to feedback nulling circuit **20** providing the nulling potential signal to a meter or recorder **38**. The nulling potential is coupled back in the feedback loop **21** via lead **40** to the substrate **15** at terminal **42**. The nulling potential is also applied to a SPV level control **44** which provides in a feedback control loop **23** a control signal to a power amplifier **46**. Power amplifier **46** is a source of variable d.c. voltage that is controlled by level control **44** to provide a particular d.c. voltage to light source **26** so as to provide light beam **16** at an intensity to provide a constant SPV for each selected wavelength of monochromatic light.

The monochromatic light carried by pipe **36** is applied to a photodetector **48**, which in turn provides a signal to a wavelength compensator **50**. A control signal representing the selected wavelength from the filter wheel or monochromator **30** is coupled to the compensator **50**. Wavelength compensator **50** provides a signal to a meter or recorder **52** representing the wavelength compensated flux I. The wavelength signal is also applied to a look-up-table such as a read only memory (ROM) **53** which, in response to the wavelength signal, provides a signal representing the coefficient α. The α signal is then applied to the meter or recorder **52** to provide a flux (I) value plotted against the coefficient α for each selected wavelength.

Filter wheel or monochromator **30**, in general, may be of the prism type or grating type. The grating type is preferred, as explained in the above-mentioned application of A. M. Goodman. Wavelength compensator **50** functions to compensate for the wavelength dependent response characteristic of the photodetector **48** due to different wavelengths, as explained in the Goodman application.

Before describing the operation of the apparatus of FIG. 3, reference is made to FIG. 4 for a further description of the details of the sensing mechanism of the surface voltage. The Kelvin probe **18** is formed of a rod of metal **18*a*** having an end piece of insulation **18*b*** and a metallic tip **18*c***. A transparent plate **18*d*** of glass or quartz is connected to the metal tip **18*c***. The bottom face **18*e*** of plate **18*d*** is provided with a transparent conducting surface **18*f*** of thin metal. The surface **18*f*** is connected to the probe tip **18*c*** by wire **54*a*** and thence, via conducting wire **54*b***, through a sealed aperture **56** for coupling the SPV to preamp **17** and thence as seen in FIG. 3 to lock-in amplifier **19**. The specimen wafer **10** is supported on conducting substrate **15** which in turn is supported on an insulator support base **58**. The wafer is contained in a housing **24** at either vacuum or low pressures, as desired.

In practice, the invention may be used in the fabrication or manufacture of solar cell wafers. Accordingly, in such uses the probe can be housed in the same chamber as the processing apparatus with suitable arrangements to position the probe **18** over the wafer when desired. Kelvin probe **18** is mounted for reciprocal movement through the housing **24** at aperture **60** and provided with suitable guides **60*a*** to allow for longitudinal movement. A flexible bellows **62** provides a resilient support of the probe **18** and seals the chamber of housing **24** from the ambient. A vibrator **64** is provided to vibrate the rod **18*a*** of the Kelvin probe **18** in vibratory vertical motions as indicated by arrow **66**. A suitable vibration frequency is about 640 Hz but the probe can be vibrated at a suitable frequency within the range of 10 to 10,000 Hz. A clamp **68** for convenience sup-

ports the fiber optic pipe 34 which receives light via lens 32 as shown in FIG. 3.

The operation of the apparatus provides a SPV voltage kept constant at each of a plurality of selected wavelengths via monochromator 30 by the electronic servo loop 21 which, in turn, provides a control signal via SPV level control 44 to vary the intensity of the lamp 26 by varying the output of power amplifier 46. The light is carried via pipe 34 to the sample surface 12 by passing through the transparent plate 18*d*. The surface-photovoltage (SPV) generated on the surface 12 of sample 10 is sensed by the vibrating Kelvin probe 18. The varying capacitance effected by probe 18 serves to couple the surface-photovoltage (SPV) to the lock-in amplifier 19 via pre-amp 17.

The amplifier 19 provides a d.c. current representing the error signal to feedback nulling circuit 20. Nulling circuit 20 responds to this d.c. current to generate a voltage of equal and opposite polarity to the potential. The negative-polarity nulling SPV is then applied via feedback path 40 to the substrate 15 carrying the wafer 10. Accordingly, the feedback loop 21 nulls the error signal with a nulling potential equal to the SPV voltage of the wafer 10. Moreover, the nulling potential from circuit 20 is applied to a meter or recorder 38 to indicate the magnitude of the SPV. It is this SPV which is kept constant for each of the plurality data points needed to determine L.

Light source 26 also provides light, via light pipe 36, to photodetector 48 which in turn after being wavelength compensated by compensator 50, at the selected wavelength of the monochromator 30, provides a compensated signal representing the flux I to meter or recorder 52. The absorption coefficient α can be determined by calculation or from a look-up table for each wavelength of incident light used to develop the SPV. In the alternative, the coefficient α can be provided automatically by a ROM 53 arranged to convert the wavelength to the coefficient α and provide a control signal to the meter or recorder 52. Recorder 52 then plots the data points 72,74 etc. (FIG. 5) needed to determine L.

The determination of L is made by the flux I (according to meter 52) being plotted on a graph as illustrated in FIG. 5, assuming that the specimen 10, identical to that tested on the apparatus of FIG. 2 described above, has a flux value of 0.9. Point 70 is plotted against, for example, a look-up table value of 0.45 μm for the reciprocal absorption coefficient of amorphous silicon at the particular optical wavelength.

A plurality of such plots are made manually or automatically for each of a group of selected wavelengths as indicated by the plotted points 72, 74, 76, 78, etc. Each of such measurements provides a flux I which value is plotted as shown for each of the points. For example, a measurement for the wavelength of the largest reciprocal absorption coefficient and flux I is represented by plotted point 78. During the measurement of each different wavelength resulting in a different flux I, the preselected d.c. SPV is kept to a substantially constant value by manually adjusting the intensity of light source 160 (as for FIG. 2) or by the servo 23 of FIG. 3 and displayed by the meter or recorder 38.

Furthermore, since the measurements at each of the selected wavelengths can be made rapidly in sequence, the effect of SPV drifting is reduced, if not minimized. In practice, a drift in the value of the light intensity I indicated by meter 52 necessary to maintain a constant magnitude SPV (as measured by meter 38) at a given wavelength should not be allowed to vary by more than about 3%. Possible inaccurate determinations of the diffusion length (L) may result if this drift value is exceeded. Such conditions may result from poor preparation of the semiconductor surface, as described in the Goodman application. Nevertheless, the magnitude of SPVs generated by using a constant illumination according to this invention, rather than chopped or modulated illumination, is substantially larger than the magnitude of the portion of the SPV that is affected by drift. Accordingly, our experiments have indicated very little if any drift effects.

Referring again to the determination of L, a line 80 is drawn through the plotted measurement points 72 . . . 78 and extended to the abscissa intersection point 82, as by the extended dotted line 84. The abscissa represents in this negative portion of the graph, the diffusion length L in micrometers. The value of 0.41 μm is determined for this exemplary plot similar to that explained for FIG. 2. In a similar manner the diffusion length L for other specimens of amorphous silicon can be determined.

It has been shown by our experimental conditions that the relation of α and I can be simply related by the expression

$$I=K\,(1\alpha+L) \qquad (1)$$

where K is a constant and α and L are as described hereinabove and as plotted in FIG. 5. Equation (1) can be used to determine L by calculation, or, if desired, used to program a simple computer arranged in FIG. 3 to replace the meter or recorder 52.

It will now be appreciated that the invention provides an apparatus and method for determining the diffusion length L of minority carriers in semiconductor material having significantly small diffusion lengths. Such material is typically amorphous silicon including hydrogenated amorphous silicon of the type used in the fabrication of solar photovoltaic devices.

While the invention is advantageously useful in determining the diffusion length of the minority carriers of amorphous silicon because such lengths are so small and, moreover, because of the very slow SPV transients, the invention is useful in general for determining the minority carrier length of any semiconductor material regardless of the magnitude of the diffusion length or the response time. The choice of whether to use the so-called chopped light technique described in the aforementioned patent application of A. M. Goodman, or the techniques disclosed hereinabove (what may be termed the d.c. light technique) depends on the conditions of use.

What is claimed is:

1. An apparatus for determining the minority carrier diffusion length of a sample of semiconductor material, the sample having two major surfaces, one of the surfaces arranged for illumination and the other surface shielded from illumination comprising:

(a) means for illuminating a portion of the one major surface of the sample with steady d.c. monochromatic light that is of a selected wavelength to provide a d.c. surface photovoltage (d.c. SPV);

(b) vibrating means positioned adjacent said illuminated surface for providing an alternating electrical signal representing said d.c. SPV on the sample;

(c) electronic servo means responsive to said alternating electrical signal for automatically providing a nulling potential equal to said d.c. SPV; and

(d) means for providing a signal representing the illumination incident upon the sample by detecting a portion of said illuminating light.

2. The apparatus according to claim 1, wherein said semiconductor material is amorphous silicon and wherein said light has a wavelength within the range of 4000 to 7000 angstroms.

3. The apparatus according to claim 1, wherein said modulated electrical signal means includes a probe having capacitance and arranged to vibrate over said illuminated surface to provide an alternating signal representing said SPV.

4. The apparatus of claim 1, wherein said modulated electrical signal means includes a Kelvin method-type probe positioned over said illuminated surface area and arranged to vibrate at a frequency within the range of about 10–10,000 Hz to provide an alternating signal representing the SPV.

5. The apparatus of claims 3 or 4, wherein said nulling means is included in a servo loop for automatically adjusting the intensity of the illuminating means at a given wavelength to generate said SPV to a substantially constant value, and means to indicate the intensity of said illuminating light.

6. A method for determining the minority carrier diffusion length of a sample of semiconductor material, the sample having two major surfaces, one of the surfaces arranged for illumination and the other surface shielded from illumination including the steps of:

(a) illuminating a portion of the one major surface of the same with steady d.c. monochromatic light that is of a selected wavelength to provide a d.c. surface photovoltage (d.c. SPV);

(b) vibrating a probe adjacent said illuminated surface to provide an alternating signal representing said d.c. SPV;

(c) providing in an electronic servo means a nulling potential equal to said d.c. SPV in response to said alternating electric signal; and

(d) providing a signal representing the illuminating intensity incident upon the sample by detecting a portion of said illuminating light.

7. A method according to claim 6, wherein the representative SPV signal is provided by positioning in the path of the light a transparent capactive pickup electrode spaced from the illuminated surface of the sample, vibrating the electrode over the surface, an alternating signal representing the SPV appearing between the transparent electrode and the surface.

8. A method according to claim 6, comprising the step of selecting the wavelength of light with a monochromator.

9. A method according to claim 6, including the step of adjusting the intensity of the illuminating light to generate a predetermined magnitude of SPV signal.

10. A method according to claim 9, further including the step of automatically adjusting the intensity of the illuminating light at a given wavelength in an electronic servo loop in response to the SPV generated on the illuminated surface of the sample to maintain the SPV to a substantially constant value.

11. A method according to claim 10, further including the step of providing in the servo loop a control signal having a magnitude and polarity to compensate for changes in the SPV signal from a predetermined value, and using the control voltage to control the intensity of the illuminating light.

12. A method according to claim 6, further including the step of detecting a portion of the light at a given wavelength to generate an electrical signal representing the photon flux illuminating the sample.

13. A method according to claim 12, further including the step of compensating at each selected wavelength of the illuminating monochromatic light for the response characteristic of the detector that is wavelength dependent.

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