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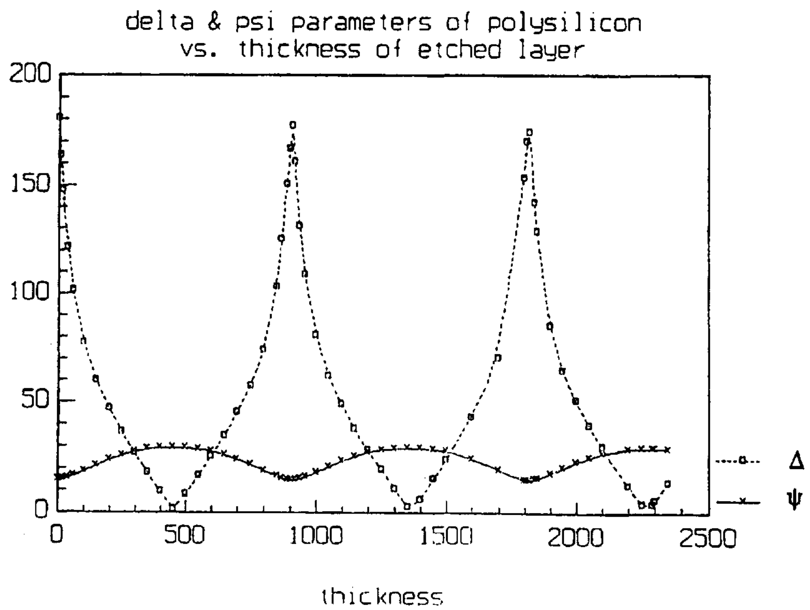
(54) Title: DETERMINING CHARACTERISTIC PARAMETERS BY POLARISED LIGHT



(57) Abstract

Plasma interaction with solid surface (during the etching or deposition) is monitored by utilising the effect of changes of state of polarisation of light. The substrate changes physical parameters during plasma processing. The monitored light is a representative of the composition of substrate surface as well as composition changes associated with plasma processing. The light reflected from the surface is analysed by a system commonly used in ellipsometry, but modified by implementation of a new method of calculation. Periodicity in state of polarisation of light is used as a reference point to monitor the occurrences on surface in real time. It is also used for quantitative and qualitative chemical analysis of the surface.

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DETERMINING CHARACTERISTIC PARAMETERS BY POLARISED LIGHT

FIELD OF THE INVENTION

THIS INVENTION relates to a method and apparatus for in-situ determination of one or more characteristic parameters of a material. In particular but not limited thereto it relates to a modified single beam ellipsometry technique for in-situ, real time determination of the one or more characteristic parameters..

BACKGROUND TO THE INVENTION

Ellipsometry is well-known as an optical technique for monitoring events at the interface between two media. In a general scheme of ellipsometry, a beam of polarised light is directed onto a changing surface. The beam interacts with the surface which results in a change in the polarisation state of the light. Measurements of the initial and final polarisation states are analysed to determine parameters describing the interaction.

In typical experimental set-up found in the prior art, a beam from a suitable light source (usually a laser) is passed through a polariser to produce light of a known polarisation. This light interacts with the optical system (surface) under study and its polarisation is modified. The modified state of polarisation is obtained by a polarisation analyser followed by a photodetector. The polarisation analyser is commonly a rotating polariser and the photodetector is commonly a photomultiplier.

Reflection ellipsometry is used for the study of surfaces and thin films. The technique can be used to determine the parameters of surface growth (eg.

Oxidation, deposition, adsorption, diffusion. etc) or surface removal (eg. Etching, desorption, sputtering, diffusion, etc).

Reference is made to "Ellipsometry and Polarised Light" by R.M.A. Azzam and N.M. Bashara published by North Holland, Amsterdam, 1977, which describes ellipsometry. Determination of parameters requires analysis of the basic ellipsometry equation:

$$\tan\psi e^{i\Delta} = \frac{R_p}{R_s}$$

where Ψ and Δ are the ellipsometric parameters given by:

$$\Psi = \arctan\frac{|E_p|}{|E_s|}$$

and

$$\Delta = \delta_p - \delta_s$$

where R is Fresnel reflection coefficient

E is electric vector

δ is phase shift

p, s are parallel and perpendicular components respectively

In essence, ellipsometry involves the measurement of tan Ψ, the change in the amplitude ratio upon reflection, and Δ, the change in phase upon reflection. These parameters are functions of the refractive index of the surface, the refractive index of the substrate, the wavelength of light used, the angle of incidence, temperature and the film thickness.

In order to determine physical properties of a material from the optical measurements a mathematical model must be used based upon the above equations. One such mode has been described by D.E. Aspnes and A.A. Studna in "Applied Optics", **14, 1, (1975) 220** and Y. Hayashi in Japanese Journal Applied Physics, **29, 11 (1990) 2514** and defines:

$$\Psi = \frac{1}{2}\arccos(-a)$$

and

$$\Delta = \arccos\left(\frac{b}{\sqrt{1-a^2}}\right)$$

The values a and b are determinable experimentally from the photodetector signals as:

$$a = \frac{1}{nI_o}\sum_{k=1}^{n} I_k(cos2A_k)$$

and

$$b = \frac{1}{nI_o} \sum_{k=1}^{n} (sin2A_k)$$

where I_0 is the average reflected intensity over one full rotation of the analysing polariser and I_κ is the measured intensity when the analysing polariser is at angle A_κ.

Each ellipsometric measurements of polarisation state change yields one value for Ψ and one value for Δ. Thus, with the best prior art techniques only two surface properties can be determined providing values for other parameters are known or assumptions are made.

Prior art methods have sought to overcome this limitation by taking multiple measurements under a variety of conditions. One such technique is described in United States Patent No. 5166752 which describes a technique for determining Ψ and Δ at a variety of angles of incidence of the laser beam. In the citation the variety of angles is achieved by directing parallel light through one or more lenses to focus the light onto the surface.

Another approach is to provide multiple ellipsometers with identical set-ups but different angles of incidence.

The known prior art techniques are not able to effectively monitor surface parameters in real time. Furthermore, there is no ellipsometric based technique that can measure etch rate/deposition rate in real time. Although current methods can measure important surface parameters they require accurate angle of incidence control and careful mechanical and optical alignment.

There is a need for an apparatus and method that can determine and/or monitor surface parameters in materials processing in-situ and preferably in real time.

OBJECT OF THE INVENTION

It is an object of the present invention to provide a method and apparatus for determining and/or monitoring one or more characteristic parameters of a material in-situ and preferably in real time during processing.

It is a further object to overcome one or more of the limitations evident in the prior art relating to determining and/or monitoring of surface properties by ellipsometry.

Other objects will be evident from the following description.

DISCLOSURE OF THE INVENTION

In one aspect therefor, the present invention resides in a method of in-situ determining and/or monitoring one or more characteristic parameters of a material during materials processing including the steps of:

directing light of known polarisation at a material;

analysing light reflected from the material to determine changes in polarisation state;

monitoring the changes in polarisation state over time to obtain a periodicity of the changes in the polarisation state; and

calculating one or more characteristic parameters of the material from the obtained periodicity.

In another aspect therefor, the present invention resides in a method of in-situ determining and/or monitoring a rate of change of thickness of a material in a surface etching or deposition process including the steps of:

directing light of know polarisation at a known material;

analysing light reflected form the material to determine changes in polarisation state;

monitoring the changes in polarisation state over time to obtain a periodicity of the changes in polarisation state; and

calculating the rate by dividing a characteristic thickness of the material derived from the obtained periodicity by time required for etching or depositing the characteristic thickness.

The step of analysing light reflected from the material may further include the step of directing the reflected light through a rotating analyser or polariser, detecting the light with a photodetector and processing signals from the photodetector in a processing means.

The step of processing signals from the photodetector in a processing means may suitably be performed in a computer using ellipsometric equations.

The calculated one or more characteristic parameters may be dependent upon one or more known parameters. In one application, if the material is known its characteristic thickness can be determined, and an etch or deposition rate can also be calculated. In another application, if the material is not known but the thickness of the material deposited or removed is known, the material can be identified. The surface temperature can also be calculated in one preferred form of the invention.

The method may further include the step of for example performing a Fourier transform on the signals form the photodetector to identity multiple signals of different periodicity.

The obtained periodicity may suitably be calculated by curve fitting techniques.

The step of directing light of known polarisation at the material may include directing multiple beams of light wherein each beam may be at a different angle, a different wavelength or both. The changes in polarisation state may then be monitored for different angles and wavelength.

In a further aspect therefor, the present invention resides in an apparatus for in-situ determining and/or monitoring one or more characteristic parameters of a material during materials processing comprising:

A source of light of known polarisation;

means for directing the light at a material;

means for analysing light reflected from the material to determine changes in polarisation state;

means for monitoring the changes in polarisation state over time to obtain a periodicity of the changes in the polarisation state; and

processing means for calculating one or more characteristic parameters of the material from the obtained periodicity.

BRIEF DETAILS OF THE DRAWINGS

To assist in understanding the invention preferred embodiments will now be described with reference to the following figures in which:

Figure 1 is schematic of an apparatus for determining and/or monitoring characteristic parameters of a wafer in plasma etching ;

Figure 2 shows a periodic nature of polarisation state with surface layer thickness;

Figure 3 shows determination of real time etch rate according to the invention;

Figures 4, 5 and 6 show determination of etch endpoint detection according to the invention.

DETAILED DESCRIPTION OF THE DRAWINGS

Referring to Figure 1, there is shown an apparatus for determining and monitoring a surface of a material during plasma etching. In this embodiment the material is a polysilicon wafer 6. The apparatus comprises a source of coherent light 1 which in this case is a laser. In the embodiment of Figure 1 the source 1 is Helium Neon laser, model LGR 7631A from Siemens. The laser has an associated power supply 2.

The state of polarisation of the incident beam 3 is determined by fixed polariser 5. The incident beam 3 may be linearly polarised, elliptically polarised or circularly polarised. Whatever the polarisation is must be fixed for the embodiment of the invention shown in Figure 1. Conceivably, the fixed polariser 5 may be incorporated in the laser 1 so that a separate element is not required.

The incident beam impinges upon the semiconductor wafer 6 at an angle φ and is reflected toward rotating polariser 7. In prior art ellipsometric methods a knowledge of the angle φ is critical. As will become evident below, knowledge of this angle is not critical in the method of the invention.

The rotating polariser 7 rotates at a known frequency determined by the modular power supply 8. In the embodiment described the polariser has two speeds, fast (3 Hz) and slow (1.5 Hz). Although a rotating polariser is preferred any element that modulates the polarisation of the reflected beam can be used.

Although the preferred embodiment is described in terms of a fixed polariser 5 and rotating polariser 7, the converse can also be used. That is, the polariser adjacent the source may rotate and the polariser adjacent the detector may be fixed. This arrangement may have advantage in a multiple beam application.

A laser line interference filter 9 filters certain optical noise from the reflected beam 10. A detector 11 produces an analog signal 12 proportional to the intensity of light incident on the detector 11. The detector 11 is energised by power supply 13. In the embodiment of Figure 1 the detector 11 is a Hammamatsu photomultiplier and the power supply 13 is a high voltage power supply.

The signal 12 is converted from analog to digital in a PCL718 A/D converter 14. The digital signal 15 is processed in a computer 16.

The apparatus can be used in various applications. In Figure 1 the apparatus is shown applied to a plasma etcher comprising a chamber 17 having an upper electrode 18 and lower electrode 19, upon which the wafer 6 is mounted. Input optical window 20 and exit optical window 21 are mounted in the chamber wall.

In one example the wafer 6 has a polysilicon layer on top of a SiO_2 layer. Polysilicon has a refractive index N_2 of 3.6 and SiO_2 has a refractive index N_3 of 1.457. The laser is adjusted for a wavelength λ of 632.8 nm and an incident angle of 70° at the surface of the polysilicon layer. Phases shift δ at the layers and Fresnel coefficients are obtained from the following equation:

$$\delta = \left(\frac{2\Pi}{\lambda}\right) N d \cos\theta$$

where N is refractive index

d is thickness

This equation is well known and is described in Azzam and Bashara referred to on page 2.

The inventor has found that the polarisation state of the reflected laser light various periodically with the change in thickness of the surface layer of the wafer 6. Figure 2 shows the periodic nature of Ψ and Δ for the polysilicon wafer 6. As can be clearly seen these parameters vary periodically with film thickness. Exemplary etched thickness G of the polysilicon layer and corresponding polarisation state values of Δ and Ψ are:

G = 0 Angstrom	Δ = 180°	Ψ = 14.59°
G = 300 Angstroms	Δ = 26.59°	Ψ = 27.23°
G = 450 Angstroms	Δ = 20.68°	Ψ = 29.24°

The apparatus described above is used to monitor the polarisation state of the reflected beam as a function of time during the etch process. Using the equations described earlier on page 4 the signals from the photomultiplier 11 are converted to polarisation state and plotted against time as shown in Figures 4 to 6. The resultant plot is periodic with the period equals to the time it takes to deposit (etch away) a characteristic quantity of the material. For polysilicon this characteristic quantity is 90 nm. Thus the etch rate (conversely the growth rate in a deposition process) is directly determinable as:

$$E_r = \frac{T_c}{P}$$

where E_r is the etch rate, T_c is the characteristic thickness and P is the time, in seconds, required for a characteristic thickness of the material to be deposited or removed.

Characteristic thickness of other materials can be determined theoretically or experimentally. Once the characteristic thickness is determined the etch rate is directly obtainable in-situ and in real time from the polarisation state periodicity.

The characteristic thickness is a function of the wavelength as well as the material. At shorter wavelengths the function of the wavelength is less for the same material. The characteristic thickness of a number of materials at a wavelength of 632.8 nm (HeNe laser) are listed in the table below. The wavelength dependence of the characteristic thickness can be exploited in complex systems as an additional degree of discrimination.

Material	Tc(nm)
polysilicon	90
silicon nitride	129.1
SiO_2	140

It will be appreciated that it is not necessary to measure an entire period before the etch rate can be determined. Curve modelling techniques can be used in the signal processing to predict the periodicity after only a few date points are obtained. The confidence level of the prediction will increase as the quality of data increases.

The etch rate can be displayed as a plot of etch rate versus plasma processing time. Such a plot in a differential mode is shown in Figure 3. Figure 3 shows etch rate versus plasma processing time plots for polysilicon and SIMOX. The plasma chamber pressure was 200mT, the gas flow was SF_6 at 20 sccm and He at 10 sccm, the power density in the plasma was 0.57 W/cm^2 RF. The measurements were taken in-situ and in real time using the apparatus of Figure 1. A knowledge of the refractive indices of the materials is not required.

It is also possible to determine differential etch rate in alloy materials or identify alloy composition from the obtained etch rates of materials. The periodicity of the changing polarisation state of an alloy will be the superposition of the periodicities of the individual components. The periodicities can be separated using Fourier transform techniques and analysed as above.

Other parameters can be determined from the experimental data. If the quantity or thickness of material removed or deposited is known the material can be identified by counting the number of periods. For example, if a plot or polarisation state against time shows 5 periods, and the total material removed is measured as 450 nm the material must be polysilicon (450 nm divided by 5 equals 90 nm which is the characteristic thickness of polysilicon).

End point can be determined by monitoring the differential change in polarisation state. Figure 4 shows a plot of

$$\frac{\partial \Delta}{\partial t} v_s t$$

where v_s is polarisation state

t is time

The end point is clearly evident.

End point can also be determined by directly monitoring the polarisation state with time. Figure 5 shows a plot of polarisation state (in this case Ψ is plotted) against time. The periodic nature of the polarisation state is clearly seen and the end point is easily identified.

Figure 6 shows a plot of polarisation state Δ against time. Again, the periodic nature of the polarisation is clearly seen and the end point is easily identified.

The method can also be applied to the measurement of the surface temperature during etching or deposition if other parameters are known. This is possible because the characteristic thickness is a function of refractive index which is temperature dependent.

The description of the preferred embodiments has generally been in terms of determining and monitoring characteristic parameters of materials during plasma etching. It will be appreciated by those skilled in the art of ellipsometer that the technique described herein is not limited to any one situation but can be applied to any surface modification process.

Although the apparatus of Figure 1 shows a single beam ellipsometer, the method and apparatus can be extended to multiple beam systems. This may be useful if monitoring of a large wafer is to occur at a number of points across the surface. In this application the rotating polariser would most conveniently be located adjacent the light source, as previously mentioned. In a multiple beam apparatus each light source may be incident at the material at a different angle and may be at a different wavelength. Multiple beams facilitates the application of the method and apparatus to complex systems.

The invention conceives that the technique can be applied to at least the following situations:

* etch rate control
* deposition rate control
* chemical composition determination
* contamination determination
* multi-wavelength analysis
* surface temperature determination
* surface homogeneity determination
* layer thickness measurement

Whilst the above has been given by way of illustrative example of the present invention, many variations and modifications thereto will be apparent to those skilled in the art without departing from the broad ambit and scope of the invention as herein set forth.

CLAIMS

1. A method of in-situ determining and/or monitoring one or more characteristic parameters of a material during materials processing including the steps of:

directing light of known polarisation at a material;

analysing light reflected from the material to determine changes in polarisation state;

monitoring the changes in polarisation state over time to obtain a periodicity of the changes in the polarisation state; and

calculating one or more characteristic parameters of the material from the obtained periodicity.

2. The method according to claim 1 wherein the light in the directing step is one or more beams of coherent light.

3. The method according to claim 2 wherein each beam is at a different angle of incidence and/or at a different wavelength.

4. The method according to any one of claims 1 to 3 wherein the light is laser.

5. The method according to any one of claims 1 to 4 wherein the light is linearly polarised, elliptically polarised or circularly polarised.

6. The method according to any one of claims 1 to 5 wherein the polarisation in the directing step or the analysing step is fixed or modulated.

7. The method according to claim 6 wherein the directing step of the analysing step includes using a fixed polarisation means for determining a polarisation state of the light.

8. The method according to claim 6 wherein the directing or the analysing step includes using a modulation means for modulating the light.

9. The method according to claim 8 wherein the modulation means is a modulation element, a rotary analyser element, a rotary polariser element or a rotary compensator element.

10. The method according to any one of claims 1 to 9 wherein the material is a solid, fluent or gaseous body.

11. The method according to any one of claims 1 to 10 wherein the material is formed of a single or plurality of substances.

12. The method according to claim 11 wherein the plurality of substances are arranged in layers or in a composite form.

13. The method according to claims 11 or 12 wherein the substances include polysilicon, silicon nitride, silicon oxide and SIMOX.

14. The method according to any one of claims 1 to 13 wherein the material is a semiconductor wafer having a polysilicon or SIMOX layer.

15. The method according to any of claims 8 to 14 wherein the analysing step includes at least one of the following further steps:

directing light reflected from the material through the modulating means,

filtering the reflecting light with a filtering means for eliminating or reducing optical noise,

detecting the reflected light with a light detection means,

converting analogue signals from the detection means to digital signals with an analogue to a digital converting means, and

processing signals from the detection means or the converting means.

16. The method according to claim 15 wherein a laser line interference filter is used in the filtering step and a processing means including a computer is used in the processing step.

17. The method according to claim 15 wherein in the processing means ellipsometric equations are used for processing the signals from the detection means or the converting means.

18. The method according to any one of claims 1 to 17 wherein the characteristic parameters include material thickness in total or in each layer, material thickness deposited or removed, a substance or substances from which the material is formed, and temperature at the material.

19. A method of in-situ determining and/or monitoring a rate of change of thickness of a material in a surface etching or deposition process including the steps according to any one of claims 1 to 18 and the further step of:

calculating the rate by dividing a characteristic thickness of the material derived from the obtained periodicity by time required for etching or depositing the characteristic thickness.

20. An apparatus for in-situ determining and/or monitoring one or more characteristic parameters of a material during materials processing the apparatus comprising.

a source of light of known polarisation;

means for directing the light at a material;

means for analysing light reflected from the material;

means for monitoring changes in polarisation state overtime to obtain a periodicity of the changes in the polarisation state; and processing means for calculating one or more characteristic parameters of the material from the obtained periodicity.

21. The apparatus according to claim 20 wherein the light is coherent and having one or more beams.

22. The apparatus according to claim 21 wherein each beam is at a different angle of incidence and/or at a different wavelength.

23. The apparatus according to any one of claims 20 to 22 wherein the light is laser.

24. The apparatus according to any one of claims 20 to 23 wherein the light is linearly polarised, elliptically polarised or circularly polarised.

25. The apparatus according to any one of claims 20 to 24 wherein the apparatus further comprising a fixed polariser means and a modulation means arranged respectively in the directing means and the analysing means or vice versa.

26 The apparatus according to claim 25 wherein the modulation means is a modulation element, a rotary analyser element, a rotary polariser element or a rotary compensator element.

27. The apparatus according to any one of claims 20 to 26 wherein the monitoring means having a filter means for eliminating or reducing optical noise in the reflected light, and a photo detector for detecting the reflected light.

28. The apparatus according to claim 27 wherein the photo detector is in the form of a photomultiplier.

29. The apparatus according to any one of claims 20 to 28 wherein the processing means is in the form of a computer.

30. The apparatus according to any one of claims 20 to 28 wherein the apparatus further comprising a plasma etching chamber having an input window through which the light is directed and an exit window for the reflected light, and an upper electrode and a lower electrode arranged in the chamber, in use the material is positioned on the lower electrode.

1/6

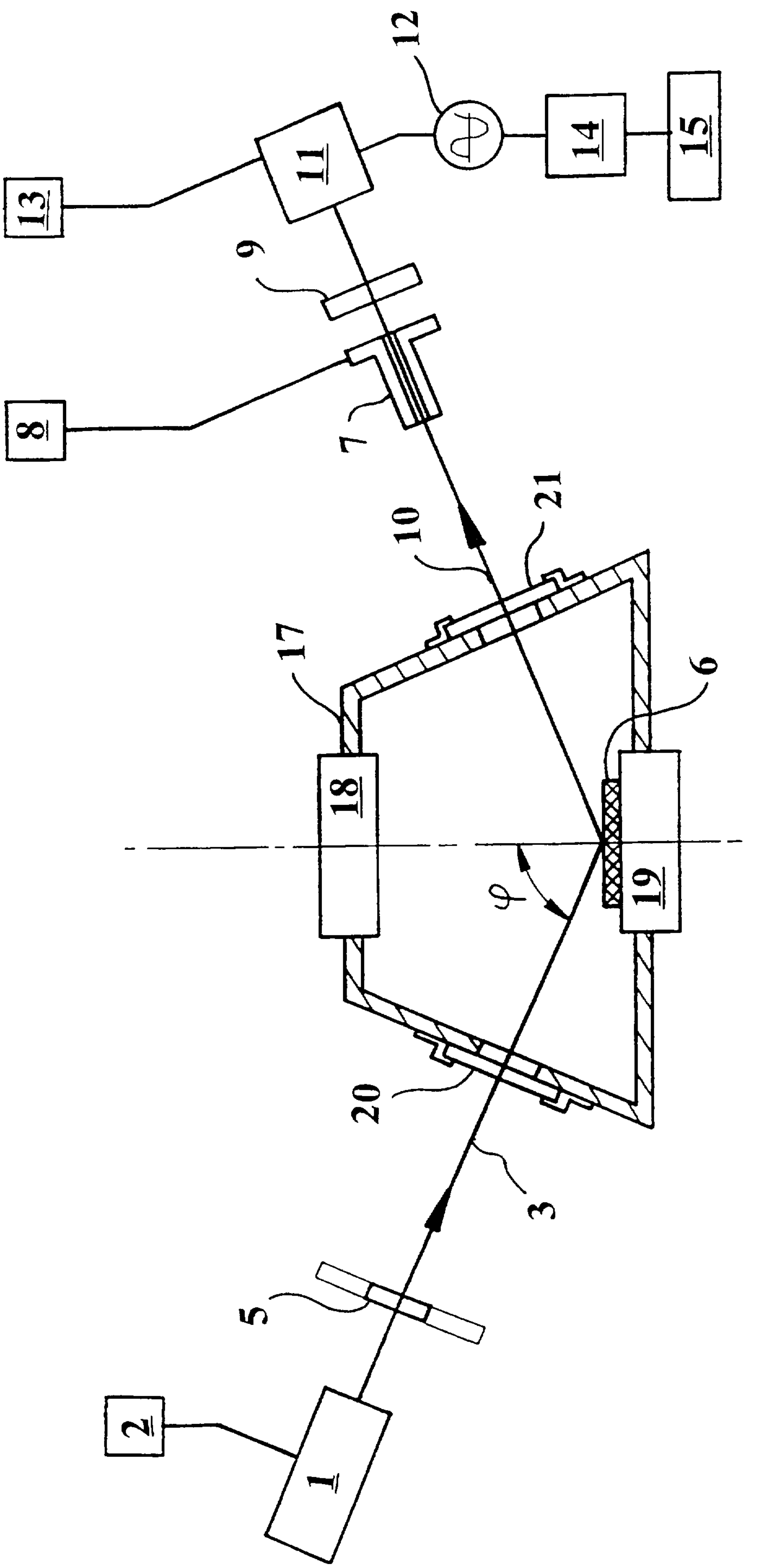

FIG. 1

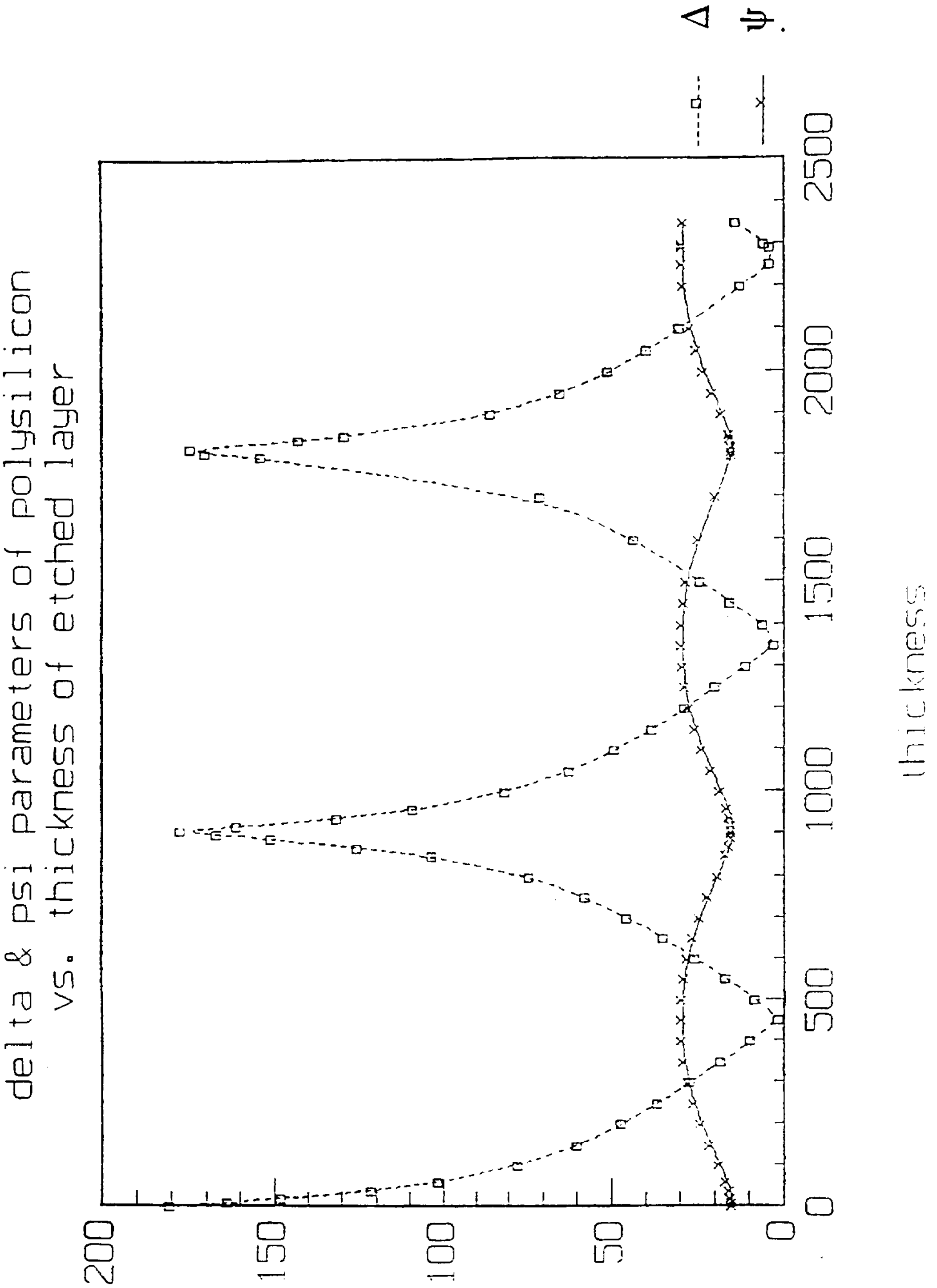
delta & psi parameters of polysilicon
vs. thickness of etched layer
Δ
ψ
200
150
100
50
0
0
500
1000
1500
2000
2500
thickness

FIG. 2

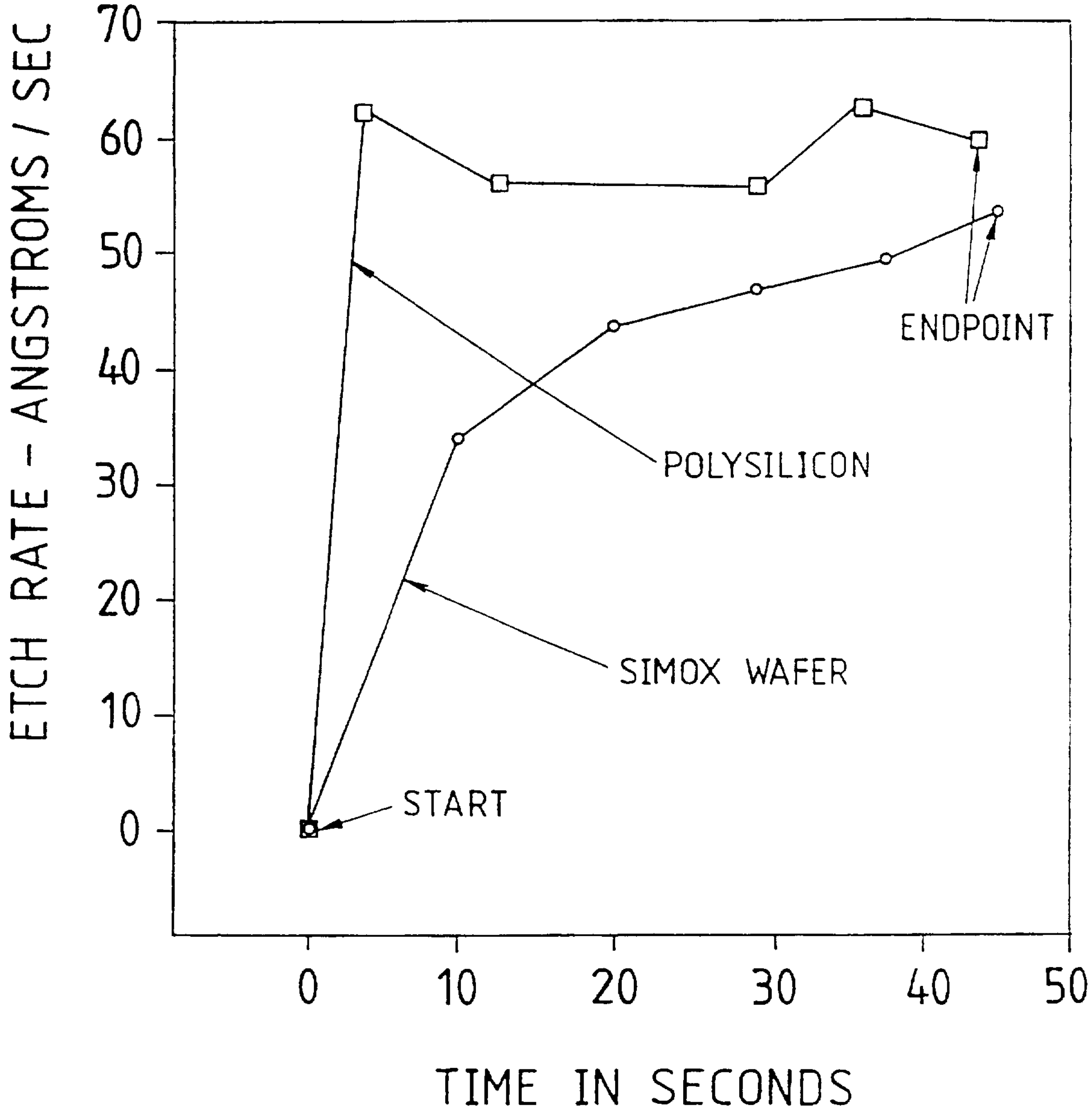
ETCH RATE - ANGSTROMS / SEC
70
60
50
40
30
20
10
0
0
10
20
30
40
50
TIME IN SECONDS
ENDPOINT
POLYSILICON
SIMOX WAFER
START

FIG. 3

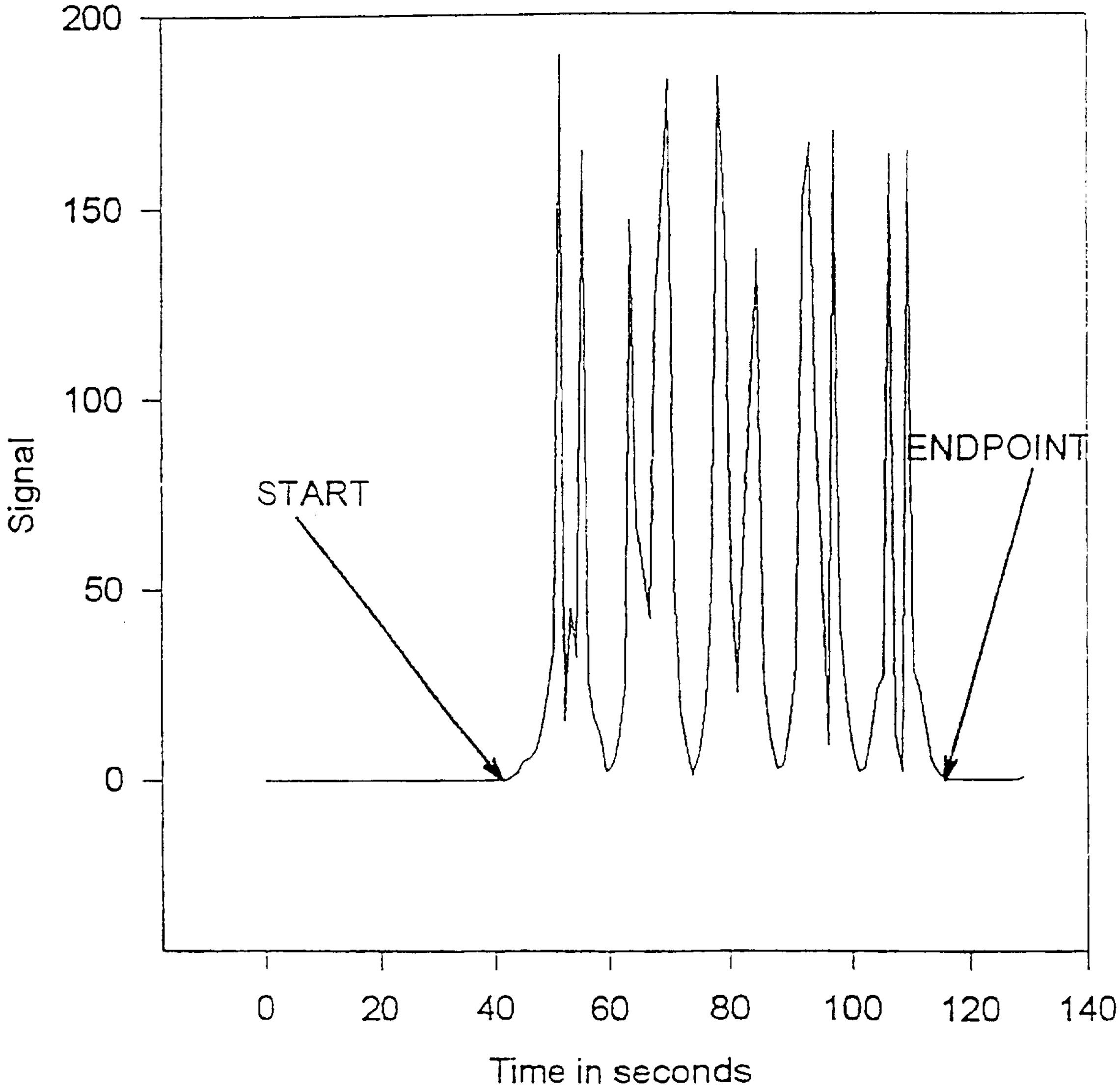
200
150
100
50
0
Signal
START
ENDPOINT
0
20
40
60
80
100
120
140
Time in seconds

FIG. 4

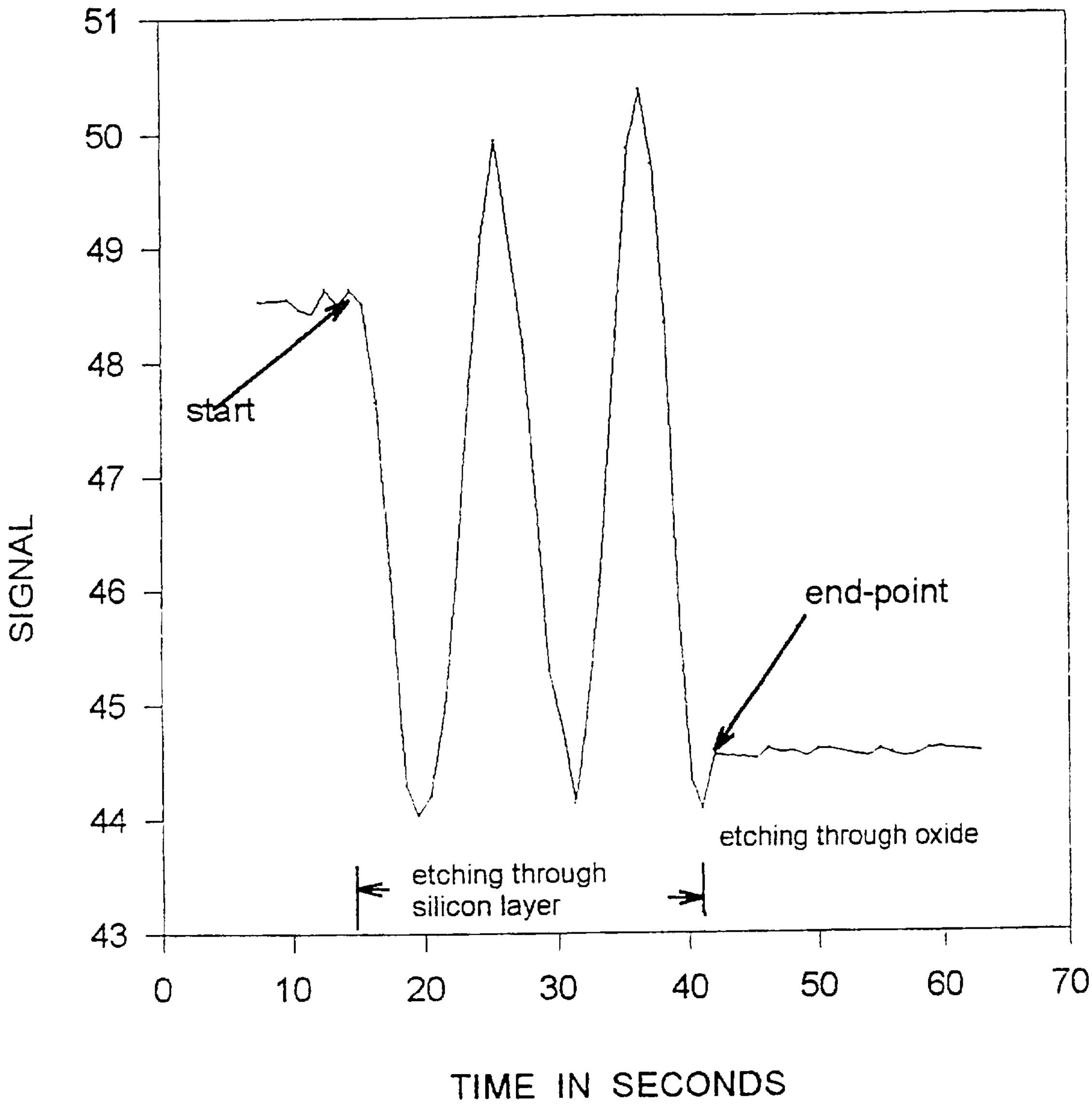
51
50
49
48
47
46
45
44
43
SIGNAL
start
end-point
etching through silicon layer
etching through oxide
0
10
20
30
40
50
60
70
TIME IN SECONDS

FIG. 5

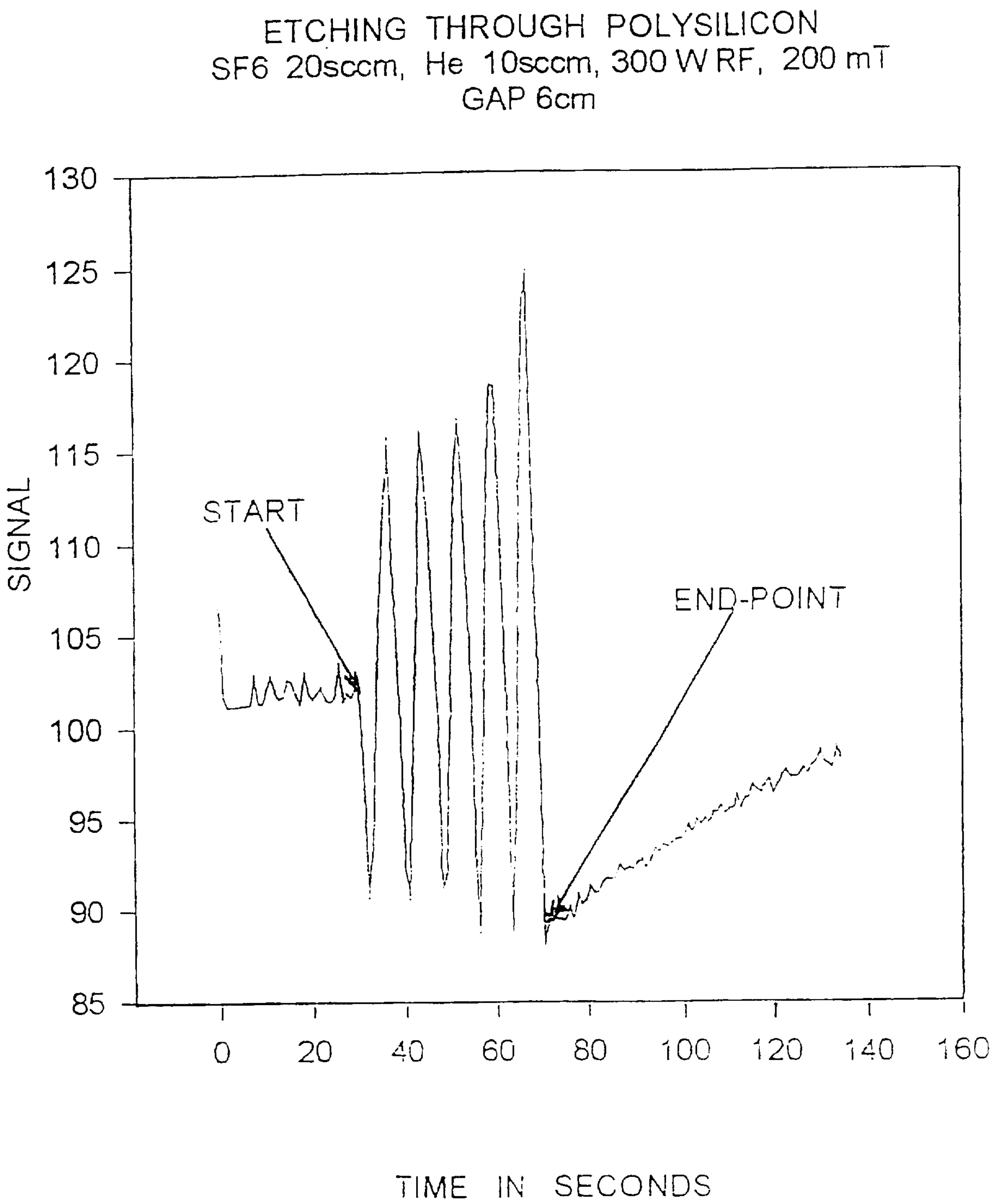
ETCHING THROUGH POLYSILICON
SF6 20sccm, He 10sccm, 300 W RF, 200 mT
GAP 6cm
130
125
120
115
110
105
100
95
90
85
SIGNAL
START
END-POINT
0
20
40
60
80
100
120
140
160
TIME IN SECONDS

FIG. 6

INTERNATIONAL SEARCH REPORT

International Application No.
PCT/AU 97/00181

A. CLASSIFICATION OF SUBJECT MATTER

Int Cl[6]: G01N 21/21, G01J 4/04

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC G01N 21/21, 21/40, G01J 4/04

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
AU - IPC as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
WPAT, JAPIO [Reflect: and (stat: or condition: or mode#)]

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 3985447 A (ASPNES) 12 October 1976 See whole document, particularly Abstract, col. 2 lines 15-45, col. 3 lines 32-55, col. 6 line 58 - col. 7 line 5	1-15, 17-30
A	US 4850711 A (SANO) 25 July 1989 See Abstract, fig. 1	1-30
A	FR 2491234 A (LABORATORIES D'ELECTRONIQUE ET DE PHYSIQUE APPLIQUEE L.E.P) 2 April 1982 See Abstract	1-30

[X] Further documents are listed in the continuation of Box C   [X] See patent family annex

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Date of the actual completion of the international search	Date of mailing of the international search report
16 May 1997	23 MAY 1997

Name and mailing address of the ISA/AU	Authorized officer
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C (Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4762414 A (GREGO) 9 August 1988 See Abstract	1-30
P, A	US 5526117 A (WIELSCH) 11 June 1996 See Abstract	1-30

INTERNATIONAL SEARCH REPORT
Information on patent family members

International Application No.
PCT/AU 97/00181

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report		Patent Family Member					
US	4850711	EP	249235	JP	62293104		
US	4762414	CA	1264959	EP	200978	IT	1184100
		JP	61259127				
US	5526117	DE	4301889	JP	6317408		

END OF ANNEX