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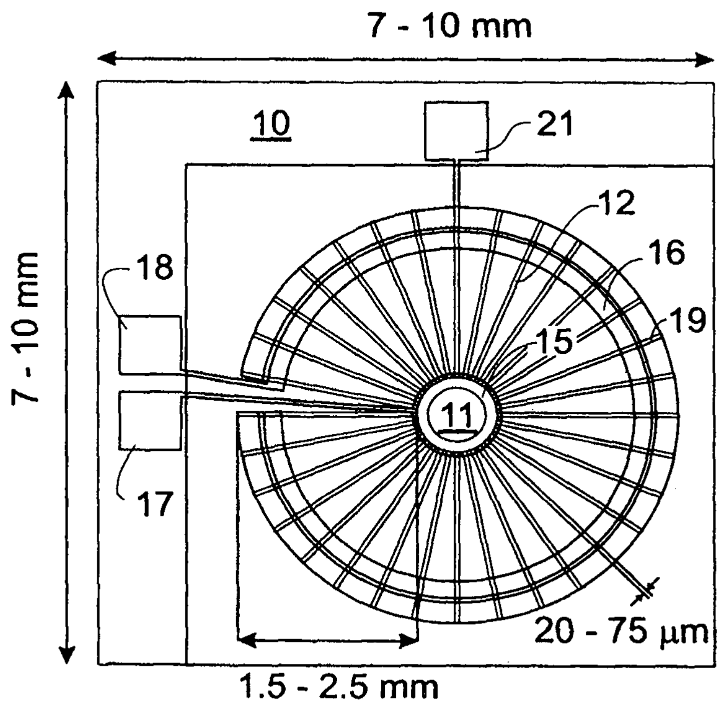
(54) Title: ELECTRON DETECTOR

(57) Abstract

An electron detector is proposed particularly for detecting secondary electrons in a micro electron column based e–beam tool such as e.g. a scanning electron microscope. The electron detector has a flat detector body (10) and a plurality of trench–shaped channels (12) extending parallel to the body surface and being e.g. open on this surface. The channels (12) extend radially from an opening (11) for the primary electron beam (1) of the tool. Furthermore, the detector comprises an inner and an outer ring electrode (15, 16) for generating an electric field which is rotationally symmetrical in relation to the axis of the opening (11) and by which the secondary electrons are accelerated along the length of the channels (12). The rotational symmetry of the electric field prevents unwanted interaction with the primary electron beam. The preferred embodiment of the electron detector is manufactured by micro–machining, starting from a silicon on insulator wafer.



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ELECTRON DETECTOR

Field of the invention

The invention relates to an electron detector according to the generic part of the first independent claim. Electron detectors are used, for example, in scanning electron microscopes (SEM) where they are employed to detect so called secondary electrons (SEs). The inventive electron detector is to be applicable in particular for the new generation of micro electron column based e-beam tools.

Background of the invention

Two kinds of secondary electrons (SEs) are distinguished depending on their kinetic energy. SEs that have less than 50 eV are called "real" SE. They originate from multiple electron-electron scattering. SEs having an energy close to that of the primaries are summarized as "back-scattered electrons" (BSEs). As the name implies, these are primary electrons that were reflected by an atom close to the surface. But also high energy Auger-electrons are sometimes referred to as BSEs. Both kinds of SE (real and back scattered) can be used for image generation in a scanning electron microscope (SEM).

The SE-current in an electron beam column can be small (fA to pA) and, hence, a direct measurement of secondary electrons, e.g. by means of a Faraday cup, is not always possible, in particular if an image is to be acquired on a reasonable time scale. Therefore, in a standard SEM, SEs are e.g. accelerated towards a scintillator-disc where they generate photons and the photons are then measured by means of a photomultiplier. BSEs being able to penetrate much deeper into the surface of the detector can be measured directly using a ring electrode or a pn- or Schottky-junction at the surface of a semiconductor detector.

However, it is not necessary to convert the SEs first into photons before detecting them. They can also be directly multiplied by means of an open-window electron-multiplier (e.g. a channeltron). These detectors work like the dynodes of a photomultiplier. They are based on work done by Goodrich and Wiley[i] and by Evans[ii]. An SE that enters the detector will hit a specially treated surface and on collision with this surface, generate additional SEs, which are again accelerated towards a further surface, and so on. An amplification of the incident current can be achieved if the SE yield σ is higher than 1. SEs emitted from an insulating material in the described manner have an energy of about 1 eV. The transverse motion of such an SE within a detector channel or tube is combined with an axial acceleration parallel to the channel length which leads to a zigzag path inside the channel and to electron multiplication on each collision with the channel wall. Multiplication of up to 10^6 can be achieved with such devices. The advantage of this method over electronic amplification is its high bandwidth.

Both channeltrons and photomultipliers need to be operated at high voltages and in high vacuum.

In standard SEM, channeltrons or photomultipliers are used for detecting SEs. The working distance (distance between the sample and the final lens of the lens system) in such devices is usually between 1 mm and about 40 mm and according to this working distance, two locations are used for detecting SEs. As shown in Figs. 1a and 1b, the detector is positioned laterally displaced from the e-beam, either at the end of the column between the sample and the final lens (bottom detector), or further upstream, inside the column (top detector). Usually, a bottom detector is used if the working distance is large enough to allow it; a top detector is used for a small working distance.

The known electron detectors as applied in standard columns and as illustrated in Figures 1a and 1b are not applicable in low energy micro-columns for two reasons. Firstly, there is not enough room for the detector neither between the sample and the column nor within the column. Secondly, the ratios of the lateral extension of the lenses to the working distance and to the column length are completely different. Therefore, there is only a very narrow slit between the sample and the final lens and deflecting the SEs to one side of this slit in the known manner would require a potential of a strength unfavorably influencing the low energy primary beam.

For detecting BSEs in micro-columns, H.S. Fresser et al.[iii] propose to use a metal-semiconductor-metal structure. For detecting both SEs and BSEs, E. Kratschmer et al.[iv] propose to use a miniature multi-channel-plate. The channels of this multi-channel-plate extend in the direction of the column axis and because of the space conditions can only have a very limited length and therefore, a correspondingly limited amplification.

It is the object of the invention to create an electron detector particularly applicable for detecting secondary electrons (real and back scattered) in micro-column based e-beam tools. The inventive electron detector is to fit easily into the tight space conditions of a micro column. It is not to influence the low energy e-beam of the tool in an unfavorable manner and it is to achieve an amplification which is satisfactory for all applications of the e-beam tool. Furthermore, the inventive electron detector is to be produceable with known methods and without causing undue problems.

Brief description of the invention

The given object is achieved by the electron detector as defined by the independent claim.

Like the above mentioned detector according to E. Kratschmer et al.[iv], the inventive electron detector works on the principle of the channeltron. It comprises means for creating an electric field and at least one channel in which electrons are accelerated by the electric field in the direction of the channel length, the at least one channel having a channel entrance and a channel end, the channel end being equipped for catching and detecting electrons and the inside surfaces of the channel being made of a material suitable for electron multiplication. The at least one channel of the inventive detector has a length extending in a plane substantially perpendicular to the primary beam of the e-beam tool and the electric field has field lines extending parallel to this plane rotationally symmetrical relative to the primary beam. Even if the detector for fitting into a micro-column has a very flat form with a thickness of less than 100 µm, the channels can have a considerable length of several millimeters and give a correspondingly high amplification.

A preferred embodiment of the inventive electron detector is made by micro-machining from a silicon wafer, i.e. by etching channels extending as open trenches parallel to the wafer surface, by coating the channel walls with a material suitable for electron multiplication (high electron yield σ) and by integrating means for creating the electric field and means (e.g. Faraday cups) for catching the electrons at the channel ends.

Such a preferred embodiment of the inventive detector has a central opening for the primary beam and it has a plurality of trench-shaped channels which are open on one surface of the die and which extend radially from the opening. A correspondingly structured metal coating constitutes ring-shaped electrodes extending coaxially around the primary beam opening and being connectable to earth and/or a suitable voltage and means for catching the electrons at the channel ends and being connectable to a suitable circuitry for quantifying the generated electron current.

Brief description of the Figures

The inventive electron detector is described in further detail in connection with the following Figures. Thereby:

Figures 1a and 1b show the spatial conditions in a standard e-beam column being equipped with a known electron detector in a bottom position (Fig. 1a) or in a top position (Fig. 1b);

Figure 2 shows the spatial conditions in a micro column and two possible locations for the detector according to the invention;

Figures 3 and 4 show a preferred embodiment of the inventive electron detector in a sectioned three dimensional representation (Fig. 3) and in a top view (Fig.4);

Figure 5 shows the physical principle of electron multiplication and detection in an inventive electron detector;

Figures 6a and 6b show the energy distribution of real SEs emitted from metals and insulators (Figure 6a) and the total SE yield σ of electrons emitted from a copper surface as a function of the energy of the electrons colliding with the surface (Figure 6b). (taken from Ref. [v])

Detailed description of the preferred embodiment

Figures 1a and 1b show in a very schematic way a standard e-beam column in section. The column comprises a primary electron beam 1, means for positioning a sample 2 in the path of the electron beam 1 and a lens system 3 for focussing the electron beam 1 on the sample 2. The working distance d (distance between the sample 2 and the final lens of the lens system 3) in such a column is usually between 1 mm and about 40 mm and an electron detector 4 for detecting secondary electrons is positioned laterally displaced from the electron beam either between the sample and the final lens (Fig. 1a, bottom detector) or within the lens system (Fig. 1b: top detector). As mentioned further above, detectors usually applied in such columns comprise photomultipliers or channeltrons.

A potential of a few hundred volts and sometimes also magnetic fields are applied to deflect real SEs (designated with SE.1) to the detector 4. The different kinetic energies of the electrons allow to separate real SEs from BSEs. The BSEs, however, can still influence this measurement. If they hit a surface of e.g. the objective lens they can generate again low energy SEs (designated with SE.2), which are then also sucked into the detector.

Figure 2 shows again in a very schematic manner the spatial conditions in a micro electron column. The column again comprises a primary electron beam 1, means for positioning a sample 2 in the path of the beam 1 and a lens system 3 for focussing the beam on the sample 2. The space 5 between the sample 2 and final lens of the lens system 3 extends laterally on all sides of the beam 1 typically by about 5 mm and has a width (working distance d) of 1 mm or less. The same as in the standard column, an electron detector 4 may be positioned between the sample 2 and the final lens of the lens system 3 as indicated by broken lines and designated with 4.1 (bottom detector) or within the lens system 3 as indicated with broken lines and designated with 4.2, provided that the detector has an extension parallel to the primary beam 1 which is not more than about 100µm and provided that it can be worked with an electric field which does not have an unfavorable effect on the primary electron beam 1. Both these conditions can easily be fulfilled by the inventive electron detector.

As mentioned further above, the detector according to E. Kratschmer et al.[v], is applicable also in the sensor positions 4.1 and 4.2 indicated in Figure 2. This detector comprises a correspondingly thin multi-channel plate with channels extending through the plate and parallel to the primary beam 1 and therefore, having a length in the order of 100 µm. It is this very restricted channel length which leads to the shortcomings of this device as discussed further above.

Figures 3 and 4 show as an example a preferred embodiment of the inventive electron detector in a sectioned three dimensional representation (Figure 3) and in a top view (Figure 4).

This electron detector has a flat detector body 10 with an opening 11 for the passage of the primary electron beam 1. At least the channel and electrode arrangement of the detector is substantially rotationally symmetrical relative to the axis of this opening

11. The channels 12 extend radial and substantially parallel to the detector body surface. They are trenches, i.e. open on the device surface, or may also be closed channels.

As mentioned above, the flat body of the inventive electron detector is preferably micro-fabricated from a silicon wafer, e.g. from a silicon on insulator (SOI) wafer comprising a silicon layer 13 and an insulator layer 14. The flat detector body 10 with the channels 12 may also be fabricated by in injection molding a suitable thermoplast.

The electric field for accelerating the electrons along the length of the trench-shaped channels 12 of the detector as shown in Figures 3 and 4 is generated between an inner ring-shaped electrode 15 and an outer ring-shaped electrode 16. The electrodes are constituted by metal coatings whereby the coating constituting the outer ring electrode 16 crosses the trench-shaped channels 12 extending without interruption across their walls and bottom, and whereby the inner ring electrode may be similar or may (as illustrated in Figure 3) extend on the surface of the flat detector body 10 radially inside the channels. The two ring electrodes 15 and 16 are advantageously each connected to a connecting pad 17 or 18 respectively.

The radially outer channel ends are designed for catching and detecting the electrons., e.g. as Faraday cups by being coated with a metal coating insulated from the outer ring electrode 16 by e.g. a ring-shaped insulation trench 20. The metal coating constituting the Faraday cups may extend as a collecting ring 19 across all channel ends and may be connected to one only connecting pad 21 (signal-out-pad). It is possible also to collect and detect the electrons in each single channel 12 or section-wise by isolating each Faraday cup from the neighboring ones and by supplying a signal-out pad for each channel or for each connected plurality of neighboring channels.

The device layer (silicon layer) used to form the channels, has a thickness of e.g. 20 or 40 μm. This thickness defines the channel depth and, to a certain degree, also the channel width (see design considerations below). The channels are etched into the device layer by means of deep reactive ion etching. The radially extending channels have a length of about 1.5 to 2.5 mm, a width of between 20 to 75μm and a depth of between 20 to 40μm.

As shown in **Figure 5** which illustrates the circuitry employed for the detector according to Figures 3 and 4, the entrance of the channels (inner ring electrode 15 or pad 17) is preferably grounded, such that, the detector potentials have the least influence on the performance of the micro-column and the acceleration potential (V_c) for generating the avalanche is applied to the channel portion opposite the entrance (outer ring electrode 16). The channel ends beyond the outer ring electrode are completely isolated from the rest of the channel. They form a kind of a Faraday cup and are connected to the signal-out pad 21. This pad 21 is on the same or on a slightly higher potential than the outer ring electrode 16 or the corresponding pad 18. This configuration allows to isolate the current I_{SE} generated by the secondary electrons from a current due to the acceleration potential V_C

The opening 11 provided in the flat detector body 10 for the primary beam 1 is preferably slightly off the center, as shown in Figure 4. When the full column is assembled, the portions containing the pads 17, 18 and 21will project from the lens assembly and can be contacted from the back side of the device via through holes. A similar design is used for contacting the individual electrodes of the lenses.

For achieving a suitable electron multiplication within the channels of the inventive detector, the detector body needs to consist of a suitable material or the inner surfaces of the channels need to be coated with such a material. This material needs to be highly resistive such as a semiconductor or an insulator and it needs to show a high yield of secondary electrons. Preferably the material is easily applicable in micro-fabrication.

Figure 6a shows the energy distribution of the real SE emitted of metals and insulators. **Figure 6b** shows the total SE yield σ for a copper surface as a function of the energy of the primary electrons colliding with the copper surface. The BSE yield is indicated by the curve η and the real SE yield by the curve δ.

Material	**Maximum Yield** σ_m	E_{mPE} in keV	E_{IPE} in eV	E_{IIPE} in keV
BeO	3.4 - 8	0.2 - 0.4	130	0.9
MgO	2.4 – 17.5	0.4 - 1.6	< 100	
Al_2O_3	1.4 – 4.8	0.35 - 1.3	37 – 40	
Pyrex glass	2.3	0.34 - 0.4	40	2.3 - 2.4
Quartz	2.1 – 2.9	0.4 - 0.44	50	2.3

Table 1 (from[v])

Table 1 shows the SE yield for a few materials suitable for the channels of the inventive electron detector together with the necessary primary energy, whereby the meaning of E_{mPE}, (maximum SE-yield) and of E_{IPE} and E_{IIEP} is the same as in Figure 6b.

Among the materials, listed in Table 1, Al_2O_3, SiO_2 (Quartz) and Pyrex are particularly advantageous for the inventive electron detector as they are commonly used in micro-fabrication. PbO_2 glass having a high secondary electron yield is used in commercially available channeltrons and is applicable for the inventive detector also.

The SE yield does not only depend on the surface material but also on the incident angle of the primary electrons. A glancing angle generates, in general, a higher yield because the electrons that are generated inside of the target are closer to the surface and, hence, can easily escape. Therefore, the effective electron yield may be increased by structured channel surfaces, consisting e.g. of a porous silicon or oxidized porous silicon. Such structuring of channel surfaces is e.g. achieved for channels which are micromachined in a silicon wafer by electrochemical etching in hydrogen fluoride

Trench-shaped channels are particularly suitable for being micro-fabricated. In order to decrease electron escape from such trenches, the trenches are advantageously as deep as possible or they are covered after micro-fabrication leaving an opening for electron entry.

The following paragraphs give an example for dimensioning the channels of an inventive electron detector as shown in the Figures 3 and 4.

Based on the values published by Goodrich and Wiley[i], a ratio of more than 50:1 for the channel length to the channel diameter should be used if a gain of 10^5 is to be reached at potentials V_C smaller than 2 keV. For a channel length of ca. 2mm as feasible in a detector according to Figures 3 or 4, this means that the channels advantageously have a width of less than 50 μm. Furthermore, Goodrich and Wiley[i] found, that for a given potential V_C, a smaller channel diameter generally exhibits a higher gain.

Electrons emitted from a channel side-wall will have an average energy of $E_\perp = 1$ eV (c.f. Fig 6a). In order to have a multiplication effect, the electrons must acquire an energy E_{PE} higher than E_{IPE} before striking the opposite wall. For an inner channel surface consisting of SiO_2, this means more than 50 eV.

Assuming a linear potential drop along the trench, the acceleration parallel to the channel length is given by:

$$m\, a_{\|} = e\, V_C/l \quad ,$$

whereby m is the mass of the electron, e its charge, V_C the voltage applied to the end of the trench, and l the trench length. The velocity perpendicular to the trench wall is:

$$v_\perp = \sqrt{(2E_\perp / m)}.$$

With d being the trench width, $v_{\|}$ can now be derived to be:

$$\begin{aligned} v_{\|} &= a_{\|}\, t \\ &= e/m\, V_C/l\, d/\, v_\perp \ . \end{aligned}$$

The total kinetic energy E_{PE} of the electron on the other hand is:

$$\begin{aligned} E_{PE} &= m/2\, (v_\perp^2 + v_{\|}^2) \\ (&> E_{IPE}.) \end{aligned}$$

From this we get a value for l/d as a function of the applied voltage V_C:

$$\frac{\sqrt{2\,(E_{PE} - E_{\perp})}}{\sqrt{m}} = \frac{e}{m}\;\frac{V_C}{l}\;\frac{d\sqrt{m}}{\sqrt{2\,E_{\perp}}}$$

$$\Rightarrow \qquad l/d = (eV_C)/\left(2\sqrt{(E_{PE} - E_{\perp})\,E_{\perp}}\right) .$$

Similarly, the required length for a certain amount n of SE impacts can be estimated. Of course this can be obtained also by:

$$n = eV_C\,/\,(E_{PE} - E_{\perp})$$

If the detector is to be operated with a commercially available video controller having a maximal output voltage of 3 kV and the amplification is to be 10^3 or higher, the following values are derived (inner channel surfaces: SiO_2):

V_C	=	3 kV	⇒	l/d	=	72
σ	=	2.9		n	=	6.8
E_{mPE}	=	440 V		max. Field	=	12 kV/cm
l	=	2.5 mm		amplification	=	1445 x

The above values show that a very high field strength is needed in order to get an acceptable amplification. This bears the risk of ionization of residual gas molecules adsorbed on the channel surfaces. This problem is well know from channeltrons and for avoiding it the channels are usually bent such reducing the risk of back-streaming ions. The same can be applied to the inventive detector by designing the channels spirally instead of straight radially.

References:

[i] G.W.Goodrich and W.C.Wiley, Electron Multiplier, U.S. Patent 3,126,408 (April 7, 1964).
G.W.Goodrich and W.C.Wiley, Continuous Channel Electron Multiplier, Rev. Sci. Instr. **32**, 761 (1962).
W.C.Wiley and C.F.Hendee, IRE Trans. Nucl. Sci. NS-9, 103 (1962).

[ii] D.S. Evans, Low Energy Charged-Particle Detection Using the Continuous-Channel Electron Multiplier, Rev. Sci Instr. **36**, 375 (1965).

[iii] H.S. Fresser, F.E. Prins and D.P. Kern, Metal-Semiconductor-Metal Structures as Electron Detector for 1 kV Microcolumns, Microelectronic Engineering **27**, 159 (1995).

[iv] E. Kratschmer et al, Journal of Vac Scienc. Technol. **B 14**, 3792 (1996).

[v] D.J. Gibbons, in: Handbook of Vacuum Physics, Vol.2, Pergamon, Oxford, pp 299-395 (1966).

CLAIMS

1. Electron detector in particular applicable for detecting secondary electrons in a micro electron column based e-beam tool, the electron detector comprising means (15, 16) for creating an electric field and at least one channel (12) with inner channel walls consisting of a material suitable for electron multiplication and with a length oriented such that electrons in the channel (12) are accelerated by the electric field from a channel entrance towards a channel comprising means (19) for catching electrons, **characterized** by means (15, 16) for creating an electric field with a rotational symmetry relative to an axis and by at least one channel (12) with a length extending in a plane substantially perpendicular to said axis.

2. Electron detector according to claim 1, **characterized** in that it comprises a flat detector body (10) with a central opening (11) for a primary electron beam (1), said axis of symmetry constituting the axis of said opening (11), and that the electric field comprises field lines extending radially from said axis.

3. Electron detector according to claim 2, **characterized** in that the at least one channel is trench-shaped being at least partly open towards one side of the flat body (10).

4. Electron detector according to claim 2 or 3, **characterized** in that the length of the at least one channel (12) extends radially or spirally from said axis.

5. Electron detector according to one of claims 2 to 4, **characterized** in that the means for creating the electric field are ring-shaped electrodes (15, 16) extending coaxially around said axis.

6. Electron detector according to one of claims 1 to 5 **characterized** in that the material suitable for electron multiplication comprises a metal oxide, a semiconductor oxide or a glass.

7. Electron detector according to one of claims 2 to 6, **characterized** in that the flat body is made of a silicon wafer.

8. Electron detector according to claim 7 **characterized** in that the means (15. 16) for creating the electric field and the means (19) for catching electrons are realized by correspondingly structured metal coatings constituting also suitable connecting pads (17, 18, 21).

9. Electron detector according to one of claims 7 or 8, characterized in that the inside surfaces of the at least one channel consist of porous silicon or of oxidized porous silicon.

10. Electron detector according to one of claims 1 to 9 characterized in that it comprises a plurality of radially extending trench-shaped channels, the channels having a length of 1.5 to 2.5 mm, a width of 20 to 70 μm and a depth of 20 to 40μm.

11. Use of an electron detector according to one of claims 1 to 10 in a micro-column as a bottom or a top detector.

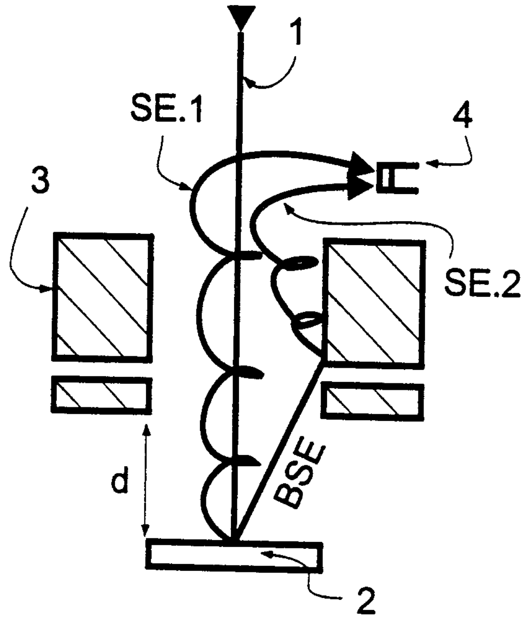

Fig. 1a

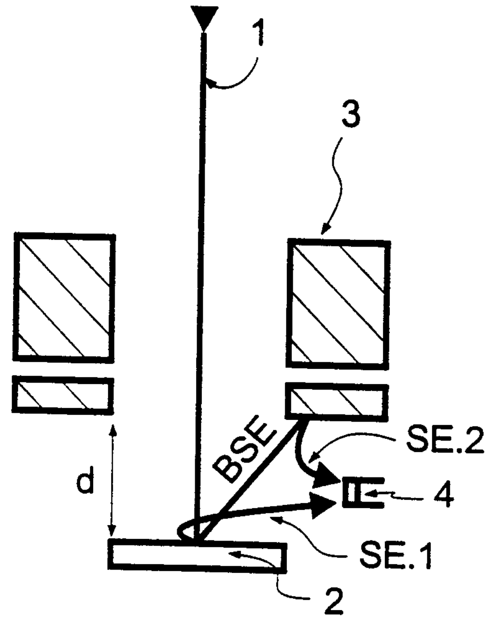

Fig. 1b

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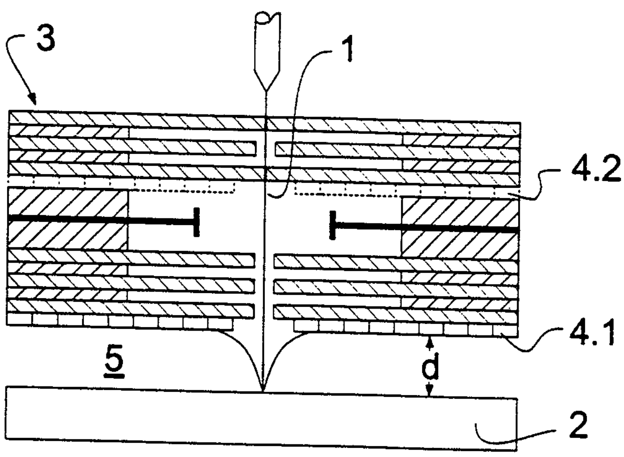

Fig. 2

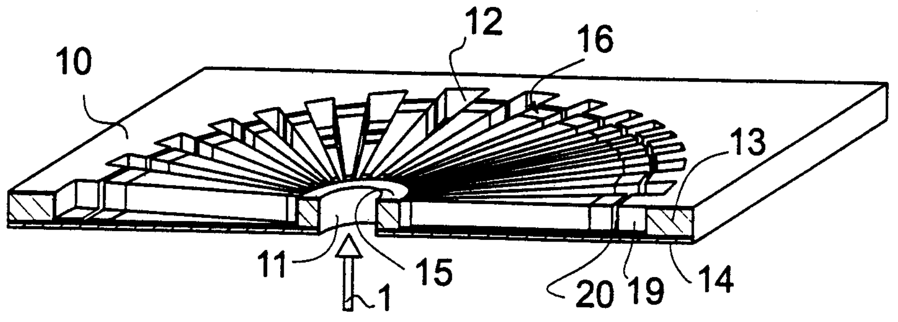
10
12
16
13
11
15
1
20
19
14

Fig. 3

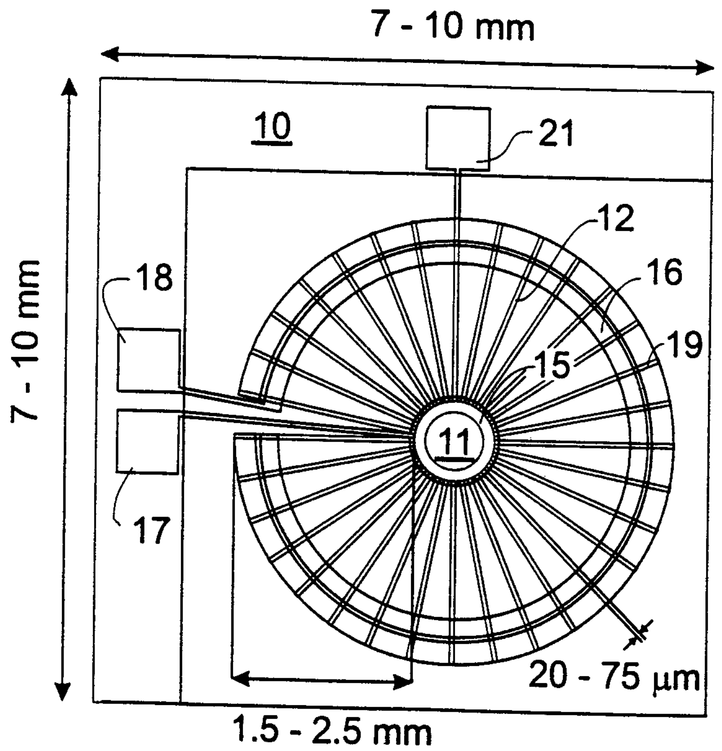
7 - 10 mm
7 - 10 mm
10
21
12
16
18
15
19
11
17
20 - 75 μm
1.5 - 2.5 mm

Fig. 4

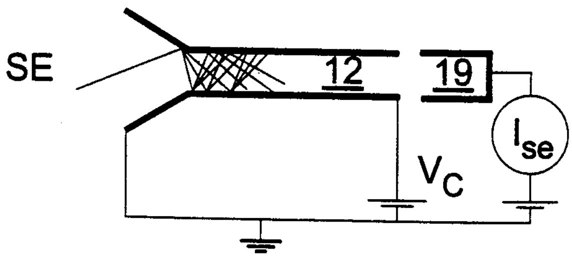

Fig. 5

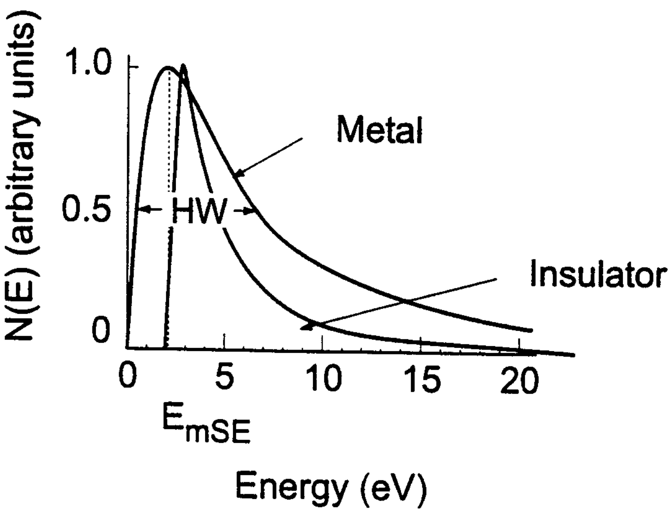

Fig. 6a

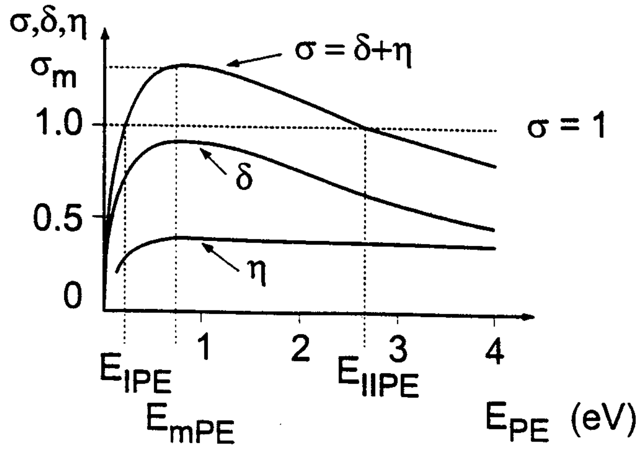

Fig. 6b

INTERNATIONAL SEARCH REPORT

International Application No
PCT/EP 99/04326

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H01J43/04

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 7 H01J G01T

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 656 807 A (PACKARD LYLE E) 12 August 1997 (1997-08-12) figures 13-17	1,6,8
A	the whole document	2-5,7, 9-11
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[X] Further documents are listed in the continuation of box C.

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4 October 1999	12/10/1999

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2

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

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