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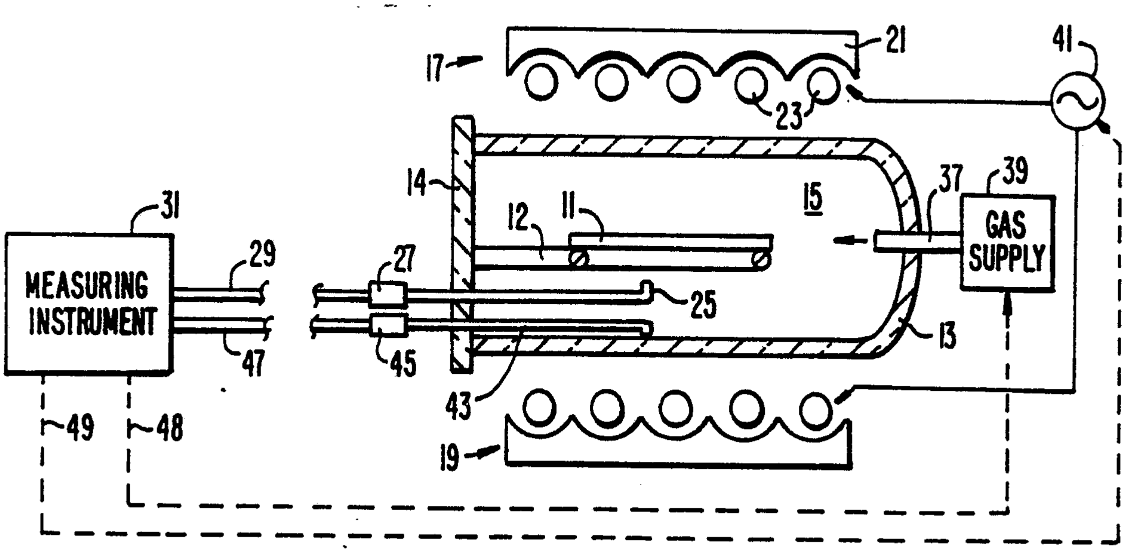

(57) Abstract

Thermal, optical, physical and chemical characteristics of a substrate (11) surface are determined with non-contact optical techniques that include illuminating (23) the surface with radiation having a ripple intensity characteristic (51), and then measuring the combined intensities (53) of that radiation after modification by the substrate surface and radiation emitted from the surface. Precise determinations of emissivity, reflectivity, temperature, changing surface composition, the existence of any layer formed on the surface and its thickness are all possible from this measurement. They may be made *in situ* and substantially in real time, thus allowing the measurement to control (39, 41) various processes of treating a substrate surface. This has significant applicability to semiconductor wafer processing and metal processing.

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NON-CONTACT OPTICAL TECHNIQUES FOR MEASURING SURFACE CONDITIONS

Background of the Invention

This invention is related to techniques of optical measurement of various conditions of solid object surfaces, such as various thermal and physical conditions of a substrate surface.

There are many examples of industrial processes where material in various forms is necessarily heated by various techniques. One example is in heating materials for the purpose of testing them. Another is in the heat treatment of an object. A further example of is found in the semiconductor processing industry. In this latter example, silicon wafers to be processed are positioned within an enclosed chamber where they are heated by some appropriate technique, usually radio frequency or optical radiation. In one form, such a semiconductor processing chamber is made, at least partially, of an optically transparent material. Lamps outside the chamber direct a large amount of energy through its transparent walls and onto the wafer. The wafer is heated as a result of its absorption of the optical radiation. Generally, the chamber is formed of a quartz envelope, or of stainless steel with an optical window. The heated wafer is treated by introducing appropriate gases into the chamber which react with the heated surface of the wafer.

These processes require that the temperature of the wafer be maintained within narrow limits in order to obtain good processing results. Therefore, some technique of monitoring the temperature of the wafer is required. One possibility is to contact the wafer with a conventional thermocouple, but this is precluded by poor measurement and contamination considerations when semiconductor wafers are the objects being heated. For other types of objects, such contact measurement techniques most often are precluded because of a number of practical considerations. Use of a thermocouple also often results in substantial errors because of a differing thermal mass, poor thermal contact and a difference in emittance between the thermocouple and the object being heated.

As a result, most optical heating applications use some form of a long wavelength pyrometer. This technique measures the intensity of the radiation of the semiconductor wafer or other optically heated object within a narrow wavelength band. That radiation intensity is then correlated with temperature of the object. In order to avoid errors by the pyrometer receiving heating optical radiation reflected from the object being heated, the wavelength chosen for monitoring by the pyrometer is outside of the emission spectrum of heating lamps. This detected wavelength range is generally made to be significantly longer than the spectrum of the lamps.

There are several disadvantages to such existing pyrometric systems. First, a measurement made at a longer wavelength will have only a portion of the sensitivity of one made at a shorter wavelength. Second, the emissivity of silicon and other materials that are optically heated is dependent upon the temperature and wavelength at which it is measured. Third, the photodetectors with the highest signal-to-noise ratio are those which respond to the shorter wavelength emissions. Fourth, existing optical pyrometers have a small numerical aperture and thus provide temperature measurements which are also dependent upon the degree of roughness of the object and film growth being measured. Fifth, existing pyrometric techniques are slow, a significant disadvantage in a rapid heating system. Sixth, measurements made through a quartz window by a typical pyrometer are subject to error as a result of a significant amount of energy that is emitted by quartz in longer wavelengths to which pyrometers are sensitive.

Therefore, it is a principal object of the present invention to provide an improved pyrometric technique of temperature and/or emissivity measurements that overcomes these shortcomings.

It is also an object of the present invention to provide non-contact techniques for monitoring and/or measuring various optical conditions of surfaces as well as thermal conditions.

There are also numerous processes involving layers of material, typically thin films, where a physical parameter, such as thickness, of the film must be measured. Usually, it is desired that a new film formed on a substrate have a desired thickness within close tolerances. Other applications involve removal of material from a layer in order to form a thin film having a precise thickness. A major application of thin film technology is also found in the manufacturing of integrated circuits, both in silicon semiconductor and gallium arsenide based technology. A typical process of forming integrated circuits in the type of heated chamber discussed above involves the formation of many films and the removal of films. It is necessary in such thin film processes to know at least when the endpoint of the film formation or removal step has been completed. It is also desirable to be able to monitor and control the process in real time by a technique that does not itself interfere with the process.

Therefore, it is also a principal object of the present invention to provide surface monitoring process having a general utility in numerous processes where thin films are utilized, such as in the manufacture of integrated circuits and in the processing of metals.

It is another object of the present invention to provide a technique for measuring the thickness of very thin films with a high degree of accuracy and high resolution.

There are also many occasions where the structure or chemical composition of a surface changes, either by accident or design, such as by its corrosion, oxidation, surface passivation, formation of rust, and the like. Generally, a layer is formed on a surface that is of a different material than that of the original surface but changes can also occur by molecules of the different material diffusing into the surface. An example of an industrial processes where this occurs is in aluminum processing where slag forms on the molten aluminum surface, or where oil is sprayed onto a surface of the aluminum being rolled. In both of these examples, the surface emissivity is unknown and changing.

Accordingly, it is a further object of the present invention to provide a technique for monitoring and measuring surface characteristics under conditions of such changes occurring.

More specifically, it is an object of the present invention to provide a method of correctly measuring a property, such as temperature, by pyrometric means despite changes in surface emissivity which unavoidably results from such surface changes.

Summary of the Invention

These and other objects are accomplished by the present invention, wherein, briefly and generally, electromagnetic radiation containing an intensity ripple is directed against an object surface of interest, the intensity of which is measured both before and after the radiation has interacted with the surface by reflection or transmission. These intensity measurements are then electronically processed in order to obtain an indication or measurement of a condition of the surface. The intensity of electromagnetic radiation emissions from the surface are also measured. The measurements are accomplished optically, without having to physically contact the surface. The measurement techniques of the present invention may be used with a wide variety of materials and processes

Many specific characteristics of a surface, or of a layer being formed on a surface, may be monitored or measured by the techniques of the present invention. These characteristics are categorized into four groups for the purpose of this discussion: (1) thermal, such as temperature or emissivity; (2) optical, such as reflectivity; (3) physical, such as layer thickness; and (4) chemical, such as the composition of a layer or surface.

An advantage of the optical/electronic measurement technique of the present invention is that measurement of one or more such surface conditions may be performed *in situ* as the object surface is naturally changing or is being processed to bring about a desired controlled change. Further, the present invention allows these measurements to be made substantially instantaneously, in real time with the changing surface being monitored. It is thus highly desirable to use these measurements to automatically control the process of changing the surface. This is of particular advantage in integrated circuit processing techniques for monitoring and controlling the formation or removal of thin films where both surface temperature and film thickness are continuously measured and the results used to control the process. It is also of advantage in metal processing, such as during heat treating of a metal, where the emissivity of the surface is changing during the process.

Additional objects, advantages and features of the many aspects of the present invention will become apparent from the following description of its preferred embodiments, which description should be taken in conjunction with the accompanying drawings.

Brief Description of the Drawings

Figure 1 schematically illustrates a particular type of semiconductor processing furnace that is equipped with a wafer measuring and control system according to the present invention;

Figure 2 provides curves that illustrate the emissivity characteristics of one type of substrate upon which a film is controllably formed by the apparatus illustrated in Figure 1;

Figure 3 is a circuit block diagram of the measuring instrument of the apparatus of Figure 1;

Figure 4 provides curves to illustrate one specific operation of the apparatus of Figure 3;

Figure 5 provides curves to illustrate another specific operation of the apparatus of Figure 3;

Figure 6 is a flow chart showing the operation of the micro-computer of the measuring instrument of Figure 4;

Figure 7 shows a modified version of the semiconductor processing furnace and measuring system of Figure 1;

Figure 8 shows another modification of the Figure 1 system;

Figure 9 illustrates desired characteristics of the light pipes used in any of the systems of Figures 1, 7 or 8;

Figures 10A, 10B and 10C illustrate three variations in the shape of an end of the light pipes used in any of the systems of Figures 1, 7 or 8; and

Figures 11 and 12 show two additional applications of the measuring techniques of the present invention.

Description of the Preferred Embodiments

Although the improvements of the present invention have application to many varied processes involving the monitoring of surface conditions, a first example to be described involves the measurement of the thermal characteristics and thickness of a film being formed or removed as a step in manufacturing integrated circuits on a semiconductor wafer. Further, although the examples deal with silicon semiconductor processes, but they are equally applicable to germanium, gallium arsenide and any other process. The resulting films are extremely thin, on the order of tenths of a micron or less, and must have their thicknesses controlled within very narrow limits. After the semiconductor processing examples are described, examples of metal processing are given herein.

Referring to Figure 1, a silicon semiconductor substrate 11 is positioned within a substantially optically transparent quartz furnace tube 13. The tube 13 and an end plate 14 form an enclosed chamber 15. The substrate 11 is supported by a quartz support 12 attached to the end piece 14, this support allowing most of the bottom surface of the substrate 11 to be exposed. Of course, there are numerous specific silicon wafer support arrangements and heated process chambers that are used in the industry, the support and process chamber of Figure 1 being generally shown only for the purpose of explaining the film measurement techniques of the present invention.

The type of semiconductor furnace illustrated in Figure 1 is that which utilizes lamps external to the chamber 15 for heating the wafer 11. Two such banks of lamps 17 and 19 are illustrated, one on either side of the wafer 11. Each has a plurality of quartz lamps, such as the lamps 23 of the light bank 17, and an appropriate reflector, such as a reflector 21. This is, however, but one example of many existing specific configurations of semiconductor furnace heating lamp configurations. The lamps are driven by an alternating current power supply 41. Gasses are introduced into the chamber 15 through an inlet 37 from an appropriate source of gas 39. What has been described so far with respect to Figure 1 is a general outline of a semiconductor reaction chamber which produces strong background radiation in the range of interest for measurement purposes in which the techniques of the present invention may nonetheless be utilized.

One type of film formed in a semiconductor process is a dielectric film. A typical dielectric is a thin silicon dioxide layer that is grown on either the silicon substrate 11 itself or some other layer of silicon based material, such as polysilicon. It is often extremely important to provide such a silicon dioxide film with the designed thickness within very small tolerances. A particular area of concern is during the formation of gate dielectrics, tunnel dielectrics, and others which are extremely thin.

Accordingly, the techniques of the present invention monitor the emissivity of the substrate surface as the film is formed on it. Since the film, having a different composition, has a different emissivity from that of the underlying substrate, the emissivity measured as a thin film is being formed is a combination of the two when the wavelengths being monitored are in the near infrared portion of the electromagnetic radiation spectrum. The changing composite emissivity is related to the thickness of the film being formed. A light pipe 25 is positioned within the chamber 15 in order to capture radiation emitted from the bottom surface of the substrate 11 on which the film is being formed. This light pipe is made of some material that can withstand the high temperatures occurring within and adjacent the furnace chamber 15, sapphire being one such material. Because of its refractive index, a sapphire light pipe also has a large numerical aperture (angle of acceptance). Cubic zirconia also has these desirable characteristics. Quartz can alternatively be used as a light pipe material. The light pipe 25 is extended a distance away from the chamber 15 to where the temperatures are cooler, and is there coupled by a connector 27 to a more common fused quartz optical fiber 29. That optical fiber is terminated in a measuring instrument 31.

Not only is the desired optical radiation emission of the substrate and forming film being communicated through the light pipe 25 to the measuring instrument 31, the light pipe 25 is also receiving optical radiation within the same infrared or near infrared radiation band from the bank of lights 19. Therefore, a second light pipe 43 is positioned within the chamber 15 and directed to capture intensity of the heating lamps 19 alone, without any direct optical signal from the substrate or film itself. This light signal is coupled by a connector 45 to an optical fiber 47 and thence provided the measuring instrument 31.

The signals in the optical fibers 29 and 47 are detected by the same type of photodetectors within the measuring instrument 31, and within the same wavelength range. The signal from the light pipe 43 is mathematically manipulated with that from the light pipe 25, thus obtaining a signal related to the optical emission of the substrate and film. That signal is then processed in a manner described below to determine the emissivity of the substrate and film. The thickness of the film is then calculated in real time from the emissivity results. These thickness determinations are then preferably used to control the film forming process, such as by adjusting the power of the lamp driving electrical source 41 through a control circuit 48 and controlling the flow or composition of gasses from the gas supply 39 into the chamber 15 by a signal in a control circuit 49. When the endpoint of a film forming process is detected by calculation of the film thickness reaching its desired magnitude, the power source 41 and/or gas supply 39 will be ramped to the end of the process. In the course of the process before reaching endpoint, the thickness measurement is also used to keep the rate at which the film is formed within specified limits by controlling the lamp power and gas supply.

Example emissivity characteristics of pure silicon are given in the curves of Figure 2. A silicon dioxide film being formed on a pure silicon wafer has a different emissivity vs. wavelength characteristic. Since emissivity is also dependent upon the temperature of the substrate and film, a wavelength range of the light pipe 25 optical signal that is detected is preferably that which is the least temperature dependent. Accordingly, a range 50 is illustrated in Figure 2, extending from about 0.8 to about 1.1 microns, selected to be slightly below the absorption band edge of about 1.2 microns of silicon. As can be seen from Figure 2, the emissivity of silicon becomes very temperature dependent when observed at wavelengths above that band edge. The detected wavelengths can be limited to the range 50 by positioning an appropriate filter (Figure 3) in the path of each of the optical signals before reaching its photodetector. Alternatively, a filter can be used that allows all wavelengths below the band gap to be detected, thereby allowing the most light to reach the photodetector but while still excluding those wavelengths above 1.2 microns. Other semiconductor materials have different band gaps, so the wavelength band selected for these measurements will be different, generally slightly below their different band gaps. In the metal processing examples described below, a wavelength range can be chosen which is slightly longer to allow measurements of lower temperatures.

Since temperature cannot totally be eliminated as a variable by wavelength selection, particularly in a general technique used with different combinations of materials, it is usually desired to also measure temperature of a substrate and film from the optical radiation signal therefrom that is captured by the light pipe 25. Both the emissivity and temperature information is then utilized to calculate film thickness. The temperature measurement is also valuable independently of the film thickness measurement, and can be used to control the temperature of the wafer or other sample within the processing chamber or area by controlling the energy supplied to the heating lamps 23 by the power supply 41.

The main functional components of the measuring instrument 31 are illustrated in Figure 3. A more detailed measuring system for a related application is described in United States Patent No. 4,750,139 - Dils (1988). Photodetectors 61 and 63 receive the optical signals from the respective optical fibers 29 and 47. These signals are first passed through optical filters 65 and 67, respectively. These filters preferably pass the same narrow bandwidth 50 (Figure 2) of optical radiation around 0.95 microns, or all wavelengths below about 1.2 microns, as discussed above, for the specific application being described. The photodetectors 61 and 63 are then preferably a commercially available silicon or indium-gallium-arsenide (InGaAs) type.

The electrical signal outputs of the photodetectors 61 and 63 are amplified by respective linear amplifiers 69 and 71. In order to time share a common analog-to-digital converter 73, a multiplexer circuit 75 is provided to alternately connect the outputs of the amplifiers 69 and 71 to another linear amplifier 77, whose output is then provided as an input to the analog-to-digital converter 73. The digitized signals are received by a microcomputer 79 and processed. The microcomputer 79 can include a very fast digital signal processing (DSP) integrated circuit chip. Part of the controlling function of the microcomputer 79 is to switch the multiplexer 75 by an appropriate control signal in the line 81.

The resulting thickness calculated by the microcomputer 79 from its input signals can either then be displayed on a display device 83 and/or utilized by control circuitry 85 to generate process control signals in the circuits 48 and 49 previously mentioned.

As an alternative to the single photodetector shown in Figure 3 for each optical channel, a pair of such detectors can be used for each channel. Each of the light pipes 29 and 47 can be coupled into a pair of smaller diameter optical fibers (not shown) that extend to separate photodetectors. One detector of each pair is coupled to a high bandwidth amplifier circuit in order to handle the a.c. ripple without distortion, and the other to a low bandwidth amplifier circuit to carry the average or mean value of the same signal. The multiplexer 75 then has four amplifier outputs as its inputs from which to choose. Part of the signal processing, namely the determination of an average or mean signal, is then carried out by the analog circuitry.

Before describing the calculations performed by the micro-computer 79 with respect to a flow chart of Figure 6, its processing of the detected optical signals is first illustrated by curves of Figure 4. A curve 51 shows the signal level output of the detector 63, corresponding to the optical signal of the lamps alone through the light pipe 43. Similarly, a curve 53 illustrates the output of the detector 61 receiving the combined object emission and heating light source reflection received by the light pipe 25. These curves represent the specific example being described since it is not necessary that the light source being used to make the measurements also be used to heat the object. Further, reflectivity and emissivity measurements can be made without detecting the infrared emissions of the object itself.

Each of the signals 51 and 53 contains a ripple (a.c.) component having a frequency of the power source 41 to the heating lamps, generally 60 Hz. in the United States and 50 Hz. in Europe, but no particular frequency is required for making the thickness and/or thermal measurements. A peak-to-peak value of the a.c. component of the signal 51 is indicated by ΔI_L, and that of the a.c. component of the signal 53 is denoted by ΔI_W. The signal levels I_L and I_W represent mean values of the signals 51 and 53, respectively. The peak-to-peak values of these signals are a small proportion of their mean values. The curves of Figure 4 also show a steady state signal 55 that is proportional to the emission of the heated object 11 (E_W), which is derived by the micro-computer processing.

Because the light pipes 25 and 43 are selected to have a very large numerical aperture, the following relationship is true.

$$\text{Wafer Reflectivity} = \rho_o = \frac{\Delta I_W}{\Delta I_L} \qquad (1)$$

Since we also know from Kirchhoff's law that emissivity of an opaque object equals one minus its reflectivity, we can state that:

$$\text{Emissivity} = 1 - \frac{\Delta I_W}{\Delta I_L} \qquad (2)$$

Equation (2) provides a measurement of the emissivity of the object. If its temperature is to be measured, the reflected component of I_W can then be subtracted away, leaving the object emission signal alone, as follows:

$$E_W = I_W - I_L\left(\frac{\Delta I_W}{\Delta I_L}\right) \qquad (3)$$

Thus, the quantity E_W is solely the thermal emission from the object and thus can be converted into temperature of the substrate 11, and the film being formed on it, by Planck's radiation law, in the same manner as with a standard pyrometer. E_W is determined from processing of the d.c. level and a.c. level of the signals 51 and 53.

Further details are provided by the applicants hereof in a paper, Schietinger et al, "Ripple Technique: A Novel Non-Contact Wafer Emissivity and Temperature Method for RTP", *Rapid Thermal and Integrated Processing*, Vol. 224, pp. 23-31, Material Research Society (1991).

A modified signal measuring technique is illustrated in Figure 5. Rather than measuring the peak-to-peak values of the lamp signal 51 and the reflected wafer signal 53, as shown in Figure 4, the microcomputer 79 of the system of Figure 3 may be programmed to integrate areas 52 and 54 under respective signal curves 51′ and 53′ with respect to their mean signal values I_L and I_W, respectively. That is, the mean values I_L and I_W are first calculated from the digital samples taken of each signal by the system of Figure 3. A absolute difference in magnitude of each digital sample with its mean signal value is then calculated, and these unsigned differences are accumulated over at least one-half of a signal sample signal cycle but preferably a large number of cycles in order to reduce the effects of any noise that may be present in the signal. These accumulated differences, or areas under the respective curves 51′ and 53′, then become the ΔI_L and ΔI_W quantities used in the subsequent calculations of equations (1), (2) and (3) above. Since the ΔI_L and ΔI_W quantities are always ratioed in these equations, it does not matter how many cycles of the respective signals 51′ and 53′ are integrated to obtain their values so long as data from the same number of cycles of is used to calculate each of ΔI_L and ΔI_W .

Referring to Figure 6, the process of the microcomputer 79 in calculating film thickness is illustrated in the form of a flow chart. Initial steps 91 and 93 determine, respectively, the a.c. component of the detected and digitized signals 53 and 51 of Figure 4. These a.c. components ΔI_L and ΔI_W can be determined by directly measuring the peak-to-peak quantities of their respective I_L and I_W signals. Alternatively, a integrated values of signals 53′ and 51′, according to Figure 6, may be used. A next step 95 is to calculate the emissivity in accordance with Equation (2) above.

A next step 97 calculates the steady state quantity 55 of Figure 4 in accordance with Equation (3) above. That steady state quantity E_W is then converted to temperature of the substrate and film by a reference table or formula empirically determined for the specific substrate and film material compositions being monitored.

At this point, both the emissivity and the temperature of the substrate 11 and film on it have been determined. Since the capabilities of microcomputers allow such calculations to occur at a rapid rate, it is preferable to make the calculations from a large sample of data in quick succession, still within a small fraction of a second, and then average those results before proceeding to calculate the film thickness from them. Thus, a step 101 of the Figure 6 flow chart keeps track of how many times the emissivity and temperature have been measured and calculated, and will continue to make such calculations until N of them have been made in succession. A step 103 averages the last N calculations. These averages are then utilized in a step 105 to convert the calculated and averaged emissivity and temperature values into film thickness. This conversion takes place by use of either a table or a formula which has been empirically determined for the particular substrate and film compositions being utilized in the process being monitored. That thickness value is then sent to an appropriate output device by a step 107, such as the display 83 or control circuits 85 of Figure 3.

So long as the monitoring continues, a step 109 then causes the calculation process to go back to the beginning and again calculate the emissivity and temperature a number N times in succession, calculate film thickness therefrom, and so on. The calculation of thickness by the process of Figure 6 can easily be made within a fraction of a second utilizing an ordinary type of microcomputer 79, thereby allowing the process illustrated in Figure 1 to be controlled in real time.

Certain adjustments and corrections in the foregoing calculations have been found to be desirable to improve the accuracy and repeatability of the measurements of the present invention under certain circumstances. The foregoing equations (1), (2) and (3) represent rather ideal circumstances, and more complex versions provide additional precision, when desired, and compensate for differences among semiconductor furnaces or other systems.

It is believed that the results obtained are affected by a number of factors, when present, such as non-uniform light intensity across the source, light entry from the sides of uncovered light pipes, light losses through the light pipe sides, and complex reflections within a chamber in which the substrate is positioned. As a result, some terms are added to the foregoing equations which are set in each case by calibration. Thus, equation (1) above becomes:

$$\rho_{adj}=\frac{\rho_o-k_2}{1-k_1} \qquad (4)$$

where k_1 and k_2 are scattering coefficients that represent the factional amount of radiance entering into the sides of the light pipes from the surrounding chamber that is redirected by scattering along the length of the light pipe. As a result, equation (2) above for determining emissivity becomes as follows:

$$Emissivity=1-\rho_{adj} \qquad (5)$$

Most of the correction, when employed, occurs in the calculation of the surface radiation emission, necessary when measurement of surface temperature is desired. Equation (3) above is modified to include three additional coefficients, as follows:

$$E_{adj}=\frac{I_W-I_Lk_2-\rho_{adj}(I_L-k_1I_L)}{A+B\rho_{adj}+C\rho_{adj}^2} \qquad (6)$$

where the coefficients A, B and C are vectors which represent shape and optical factors and can be temperature dependent. The polynomial of the denominator of equation (6) can be expanded to include higher order terms when the reflectivity of the chamber is low.

These five constants and coefficients are determined for a particular furnace, or other type of system, by a calibration procedure. Calibration of the measuring system for use in a semiconductor processing furnace chamber of the type shown in Figure 1 is described as an example. A first step is to calibrate its light pipes and photodetectors in an environment outside of the furnace chamber in order to be able to accurately measure the emissivity of test object surfaces during a second calibration step. In this first step, the radiation emission of a test blackbody is gathered by a light pipe and photodetector from the system being calibrated but outside its furnace chamber. The output of the photodetector is then measured with the blackbody heated to different temperatures by non-optical techniques. The temperature of the blackbody is accurately measured by embedding a thermocouple in it. Since the test blackbody has an emissivity of one, the data gathered of the photodetector output as a function of temperature provides reference data for determining the emissivity of other object surfaces.

As a second calibration step, the emissivity of an object surface of a type likely to be processed in the furnace chamber is accurately measured outside of the furnace, without any heating lamps, by the light pipe and photodetector combination that was calibrated in the first step. A thermocouple is embedded in this object surface as well. It is heated by some appropriate technique that does not affect the optical measurements being made. The emission of the object is measured by the previously calibrated light pipe and detector system at the same temperatures as in the first calibration step. The photodetector outputs in this step will be less than those in the first calibration step because the object surface is not a blackbody. A ratio of the photodetector outputs obtained during the first and second calibration steps at the same temperatures gives the object surface emissivity, if the light pipe and photodetectors are linear. If not linear, some appropriate correction is first made.

As a third step in the calibration procedure, the calibrated light pipe and photodetector system is placed into the semiconductor furnace in which it is to be used. The same substrate that was measured in the second step is also placed into the furnace chamber. The geometric relationship between a substrate holder and the light pipes is maintained the same in the second and third calibration steps, being that used in the furnace chamber after calibration is complete. The temperature of the substrate surface is again accurately monitored by keeping the thermocouple embedded in the substrate. Measurements are then made by the entire system as the substrate is increased in temperature through the various levels where the emissivity of the substrate surface is known from measurements made in the second calibration step. The furnace or other system is operated as it is intended to be operated when the calibrated system is relied upon to make its measurements, including use of its heating lamps to raise the substrate temperature. The emissivity and temperature values calculated from equations (5) and (6) above are then compared with the emissivity measured in the second calibration step and the temperature being measured by the thermocouple. The calculated values will likely be different to some degree from the measured values. It is the purpose of the calibration procedure to adjust the calculations being made to eliminate these differences. After enough such measurements are made, the values of k_1, k_2, A, B and C of equations (4), (5) and (6) can be mathematically be determined which will cause the calculated characteristics of the substrate surface to agree with the measured values, for that particular object surface, with increased precision compared to operating the system without this calibration being done.

Such a calibration is accurate only for one specific substrate surface, however. In order to calibrate the system more completely, steps two and three above are repeated for a number of different types of substrate surfaces. Enough data is then obtained to fix each of k_1, k_2, A, B and C at single values that will provide accurate results by use of equations (4), (5) and (6) for a wide range of substrate surfaces. Additionally, it may be desirable to add another calibration step where all the measurements described above in step three are made within the chamber but with the heating lamps off, some non-optical means being used to heat the substrate for the purpose of making another set of calibration measurements.

A modification of the system of Figure 1 is illustrated in Figure 7, where corresponding elements and components are identified by the same reference numbers but with a prime (′) added. The primary difference is the positioning of light pipes 25′ and 43′ on the outside of the quartz furnace tube 13′. Thus, the light pipe 25′ receives emissions and reflected radiation from the substrate 11′ through a wall of the tube 13′. The light pipe 43′ receives radiation from an optical lamp without any component from within the furnace tube 13′. The difference in the Figure 7 arrangement is that the optical signals thus detected are somewhat different than those detected within the chamber 15′ by the embodiment of Figure 1, that difference being a filtering effect caused by the quartz or other material used to make the material 13′.

The example semiconductor processing furnace systems of Figures 1 and 7 are of a type utilizing lamps to heat the semiconductor wafers within the processing chamber to the required temperatures where the necessary chemical reactions can take place. This is convenient for application of the techniques of the present invention since a necessary a.c. driven light source already exists. However, there are different techniques for heating semiconductor wafers, such as using a radio frequency generator or resistance heating, where the light source is not available for use in deriving data necessary to make the film thickness calculation. Further, in fields other than in integrated circuit processing, such heating lamps are likely not utilized. In such circumstances, therefore, it is necessary to direct optical radiation against the substrate surface on which a film is being formed or an unknown emissivity is being measured.

Such a system is schematically illustrated in Figure 8. An additional sapphire light pipe 111 carries to the subject surface of a substrate 11′′ optical radiation from a light source 113 that is energized by an alternating current source 115 of any convenient frequency. It may be desired in certain applications to choose a frequency that is distinct from any ambient light having an alternating intensity component. On the other hand, general building lighting, available from either fluorescent or incandescent sources that are permanently installed, may be used in place of the dedicated light source 113 and light pipe 111 when the application permits. The reflected radiation and emissions from the substrate and film are than gathered by the light pipe 25'', corresponding to the light pipe 25 of Figure 1, and a signal proportional to the intensity of the light striking the substrate 11'' is captured by the light pipe 43'', corresponding to the light pipe 43 of Figure 1. Such a system is made practical with the large numerical aperture of the preferred sapphire light pipes.

The wide angle of acceptance of such light pipes results in collecting light that has passed through the film at various different angles, thus traveling through the film with a range of different path lengths. Any variation in intensity level of light passing through the film along any one path that is due to interference effects within the film as it increases in thickness will be different than those variations of light traveling in another path. When all these rays are directed onto a single detector, an averaged signal results which minimizes such interference effects on the emissivity being measured.

Another way to minimize such interference effects is to separately detect in two wavelength bands light passing through the film with a reduced range of angles, such as by directing only central rays of a light pipe onto a photodetector. In the silicon substrate example given above, the second wavelength range would also be less than the 1.2 micron band edge and separated significantly in wavelength from the first range. The bands are kept separate by appropriate beam splitting and filtering with a single pair of light pipes as illustrated herein, or can alternatively utilize an additional pair of light pipes having filters which select the second wavelength band. Also, because of the narrow angle of optical acceptance which is necessary, a traditional optical system, such as a pyrometer, may be substituted for the light pipe.

Yet another way to minimize such interference effects within the film is to separately detect the light passing through the film in at least two different angles with respect to its surface. This can be accomplished by using the large numerical aperture light pipe discussed above but then optically directing its central and outer modes onto different photodetectors. Alternatively, rather than such using a light pipe, two traditional pyrometers may be utilized by directing them at different angles toward the same spot on the substrate surface upon which the film is being formed.

With reference to Figures 9 and 10, light pipe structures are shown which increase and control the aperture of one or both of the electromagnetic radiation gathering light pipes in the systems shown in Figures 1, 7 or 8. The already wide angle of acceptance of the light pipe, brought about by its high refractive index, is increased by shaping its end to include a lens element. The usual light pipe end, which is planar in a direction perpendicular to a longitudinal axis of the light pipe, is reshaped to provide a domed, convex surface that increases the field of view of the light pipe without having to provide a separate optical system.

Such a modification is particularly preferred for the light pipe 43 that is used to gather radiation from the heat lamps in the system of Figure 1, or in different situations where other lamps are used that do not heat the object. It has been found to be desirable to gather the reference light signal through the light pipe 43 over approximately the same area of the light source that is illuminating the portion of the wafer 11 supplying reflected light into the light pipe 25. The wider aperture also gathers more light reflected from internal surfaces of the chamber 15, important because the portion of the wafer being viewed through the light pipe 25 is also illuminated by these reflections.

Figure 9 illustrates such a modified light pipe 121 having an approximately spherically shaped convex surface 123 at its light gathering end. Figure 10B shows an expanded view of this light pipe. A cone 125, shown in Figure 9 in dotted outline, indicates a field of view of a light pipe with a planar end, in order to provide a comparison with an increased field of view, indicated by the cone 127, that results from shaping the light pipe end into a dome 123. Radiation from heating lamps 129 is then gathered over a larger portion of a lamp area that is irradiating a portion 131 of a wafer 133 from which a second light pipe 135 receives reflected light. The second light pipe 135 corresponds to the light pipe 25 of the Figure 1 system.

Figure 10A illustrates the relative size of the cone 125 that represents a field of view of a typical light pipe 137 with a planar end 139. This can be compared with the cone 127 of the improved light pipe end 123 shown in Figure 10B. The domed end 123 may be formed from a planar end of a light pipe by either mechanically or flame polishing the end. The material preferred for the improved light pipes remains the high refractive index, high melting point materials previously mentioned, namely sapphire, cubic zirconia or quartz. A further alternative modification is given in Figure 10C, where an end 141 of a light pipe 143 is formed into ball shape to even further increase its field of view 145.

Another technique for increasing the field of view of the light pipes is to properly couple each of them optically to their respective optical fibers.

Referring to Figure 1, as an example, the light pipes 25 and 43, having a very high index of refraction, are coupled into respective quartz optical fibers 29 and 47, having a lower index of refraction, by couplers 27 and 45. Because of the much different indices of refraction, the angle of acceptance of the optical fiber is much less than that of the light pipe to which it is coupled. The result is that not all the light captured by the light pipe is coupled into its respective optical fiber. In order to overcome this, an optical element or a simple optical system is provided as part of each of the couplers 27 and 45 to couple as much of the light intensity as possible from the light pipe into the optical fiber. One embodiment of this is a lens that images the light output of the light pipe into the optical fiber. Alternatively, a diffuser or mode mixer can be employed.

As stated previously, the techniques of the present invention are useful in many surface measurement applications other than semiconductor processing, both with surfaces that are being heated and those that are not. Figures 11 and 12 generally illustrate two such additional applications. In Figure 11, a quantity of molten metal 151 is carried by a crucible 153. An incandescent or fluorescent light source 155 directs light against the surface of the metal bath 151 for the purpose of making a measurement of any of the physical, thermal or optical characteristics discussed above for that surface. The light source will usually not have a purpose of heating the metal bath 151 but could do so if desired. A light pipe 157 gathers some of the emission of the light source 155 and communicates it by way of an optical fiber to a measuring instrument 161 of the type described with respect to Figure 3. Similarly, a light pipe 163 gathers some of the light that is reflected from the top surface of the molten metal 151 and communicates that light signal through an optical fiber 165 to the instrument 161.

The emissivity of the surface of the molten metal 151 is usually unknown, and further will generally be changing as a result of its processing. Oxidation is one such change. Another results from treatment of the surface by the addition of a film or layer of some other material. The measurement techniques of the present invention are particularly valuable in such difficult situations where conventional non-contact, optical techniques will not operate properly.

In Figure 12, a moving sheet 167 of aluminum or other metal is moving past a surface characteristic measurement station. That measurement station includes a light source 169 positioned above the path of the sheet material 167. The source 169 is shown as a single standard fluorescent light tube but can be of some other form so long as its light output has the ripple intensity component discussed above. A light pipe 171 collects a portion of the source output and carries it by an optical fiber 173 to a measuring instrument 175. Another light pipe 177 carries a portion of that light, after reflection by the surface of the material 167, to the instrument 175 over another optical fiber 179. This system provides a real time measurement of any one of many characteristics of the material surface in a manner that allows processing of the metal 167 to be controlled, at least in part, by the measured results.

Although the various aspects of the present invention have been described with respect to their preferred embodiments, it will be understood that the invention is entitled to protection within the full scope of the appended claims.

IT IS CLAIMED:

1. A method of determining a physical or chemical characteristic of a layer of one material on a surface of another material, comprising the steps of:

directing electromagnetic radiation toward the layer and surface in a manner to be modified thereby, said radiation including a given wavelength range and having a periodic intensity ripple,

detecting a level of the intensity of the given wavelength range of the electromagnetic radiation modified by the layer, thereby to generate a first electrical signal having a periodic intensity ripple of a first magnitude,

detecting the intensity of a portion of the electromagnetic radiation within said given wavelength range that is being directed toward the layer and surface, thereby to generate a second electrical signal having a periodic intensity ripple of a second magnitude, and

determining the physical or chemical characteristic of the layer and surface from magnitudes of the ripple components of the first and second electrical signals.

2. The method according to claim 1 wherein said surface includes a semiconductor material, and wherein said given wavelength range lies below an absorption band edge of the semiconductor substrate.

3. The method according to claim 1 wherein said surface includes a metal undergoing heat treating.

4. The method according to claim 1 wherein at least one of the radiation detecting steps includes the steps of gathering the electromagnetic radiation in a light pipe made of any one of quartz, sapphire or cubic

zirconia, and directing the gathered radiation onto a photodetector.

5. The method according to claim 3 wherein at gathering step includes gathering the electromagnetic radiation through an end of a light pipe convexly shaped, thereby to increase its field of view.

6. The method according to claim 1 wherein the determining step includes taking a ratio of the time varying component magnitudes of said first and second signals.

7. The method according to claim 6 wherein the determining step includes the step of measuring the time varying component magnitudes of by integrating the first and second signals with respect to respective mean values of said signals.

8. The method according to claim 6 wherein the determining step includes the further step of subtracting said ratio from one, thereby determining a quantity related to emissivity of the surface.

9. The method according to claim 6 wherein the first electrical signal detecting step additionally includes detecting and including in said first electrical signal the intensity of electromagnetic radiation that is emitted from the film and surface within the given wavelength range.

10. The method according to claim 9 wherein the determining step includes the additional steps of multiplying said ratio by one of said first and second signals and then subtracting the result from the other

of said first and second signals, thereby determining a quantity related to temperature of the surface.

11. The method according to claim 6 wherein the determining step includes the additional steps of multiplying said ratio by the second signal and then subtracting the result from the first signal.

12. The method according to any one of claims 1-11 wherein the physical or chemical characteristic being determined includes a thickness of the layer.

13. The method according to any one of claims 1-11 wherein the physical or chemical characteristic being determined includes a composition of the layer or surface.

14. The method according to claim 1 wherein the physical characteristic determining step is caused to occur simultaneously as the layer is being formed on the substrate surface.

15. The method according to claim 14 which comprises an additional step of utilizing the layer thickness determination to control a process of forming the layer on the surface.

16. The method according to claim 1 wherein the step of directing optical radiation against the layer and surface includes use of a set of heating lamps driven by alternating current, thereby to heat the layer and surface by such lamp illumination.

17. The method according to claim 1 wherein the radiation directing step includes positioning the

surface in the path of illumination from permanently installed building incandescent or fluorescent lamps.

18. A non-contact method of determining a characteristic of a surface, comprising the steps of:

directing against said surface incident electromagnetic radiation having a time varying component, wherein a portion of said incident radiation is reflected from said surface with such a time varying component,

detecting as a first electrical signal a combined level of said reflected portion of the incident electromagnetic radiation and electromagnetic radiation that is emitted from said surface,

detecting as a second electrical signal a level of the incident electromagnetic radiation that is being directed against said surface,

determining a mean value of each of the first and second electrical signals,

integrating each of the first and second electrical signals with respect to their respective mean values, thereby to provide a value of a time varying component in each of said first and second signals, and

combining at least the time varying component values of said first and second signals in a manner to obtain said surface characteristic.

19. The method according to claim 18 wherein the combining step includes taking a ratio of the time varying component values of said first and second signals.

20. A system adapted to measure a characteristic of a surface of an article, comprising:

a source of electromagnetic radiation that contains a time varying ripple component, means for directing said source electromagnetic radiation against said article surface,

first and second photodetectors each characterized by generating an electrical signal proportional to the level of electromagnetic radiation incident upon it,

means positioned with respect to the article for carrying to the first photodetector both a portion of source optical radiation reflected from said article surface area and optical radiation emitted by said article surface area within the bandwidth of the source optical radiation,

means positioned with respect to the source for carrying to the second photodetector a portion of source optical radiation substantially without any radiation reflected or emitted from said article surface, said source carrying means including an elongated light pipe having a solid end thereof with a convex shape that is oriented to gather source radiation therethrough, and

means receiving and combining the electrical signals from the first and second photodetectors for determining the temperature and/or emissivity of the surface.

21. The system according to claim 20 wherein said article radiation carrying means includes a second elongated light pipe having a solid end thereof with a convex shape that is oriented to gather therethrough radiation reflected and emitted from said article surface.

22. The system according to claim 20 wherein said light pipe consists essentially of material from one of a group of sapphire, cubic zirconia and quartz.

23. In a system for forming a layer of material on a substrate surface that is positioned within a chamber having a substantially optically transparent window in a wall thereof, wherein said substrate is heated by directing electromagnetic radiation of a given bandwidth against said substrate through said window from outside of said chamber from an electromagnetic radiation source that is characterized by a time varying intensity component, an improvement adapted to monitor formation of said layer, comprising:

first and second photodetectors, each of said photodetectors being characterized by generating an electrical signal proportional to a level of electromagnetic radiation incident thereon that includes said time varying intensity radiation component,

means positioned with respect to the substrate surface for carrying to the first photodetector both a portion of source electromagnetic radiation reflected from said substrate surface area and electromagnetic radiation emitted by said substrate surface area within the bandwidth of the source electromagnetic radiation, thereby to generate a first electrical signal that contains a first time varying component,

means positioned with respect to the source for carrying to the second photodetector a portion of source electromagnetic radiation substantially without any radiation reflected or emitted from said substrate surface, thereby to generate a second electrical signal that contains a second time varying component, and

means receiving said first and second electrical signals for determining the thickness of the layer by at least combining magnitudes of the first and second electrical signal time varying components.

24. The system of claim 23 wherein said first and second photodetectors are positioned outside of said

chamber, and wherein said first and second photodetector radiation carrying means include respective first and second light pipes that each have one end thereof positioned within said chamber.

25. The system of claim 23 wherein said first and second light pipes are made substantially entirely of either sapphire or cubic zirconia material.

26. The system of claim 24 wherein at least one of said first and second light pipes includes a solid end thereof that is convexly shaped and positioned to receive radiation therethrough.

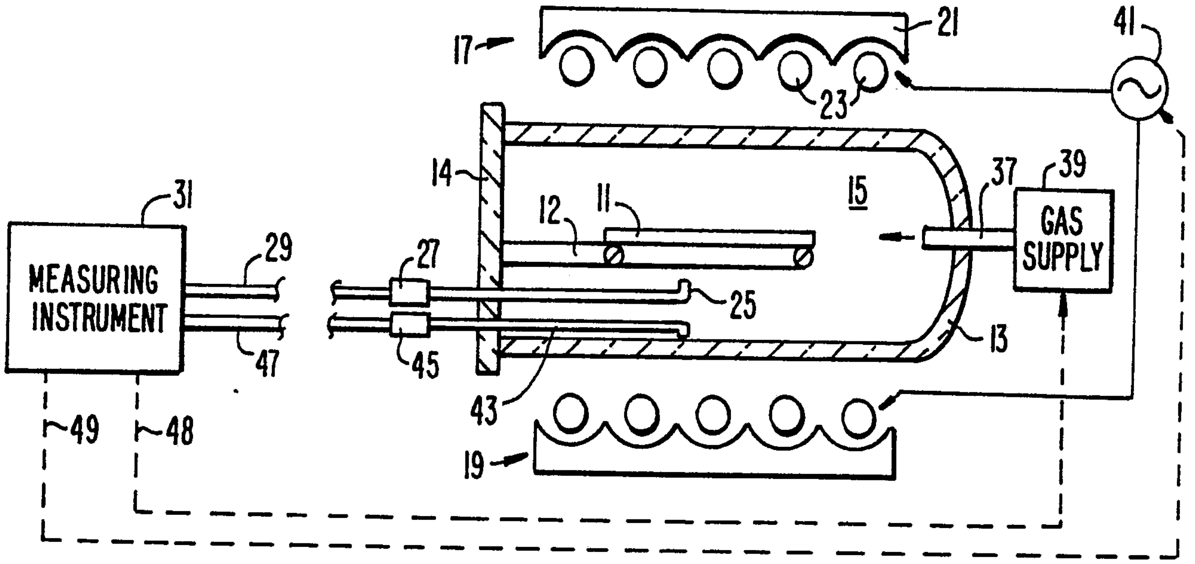

FIG. 1.

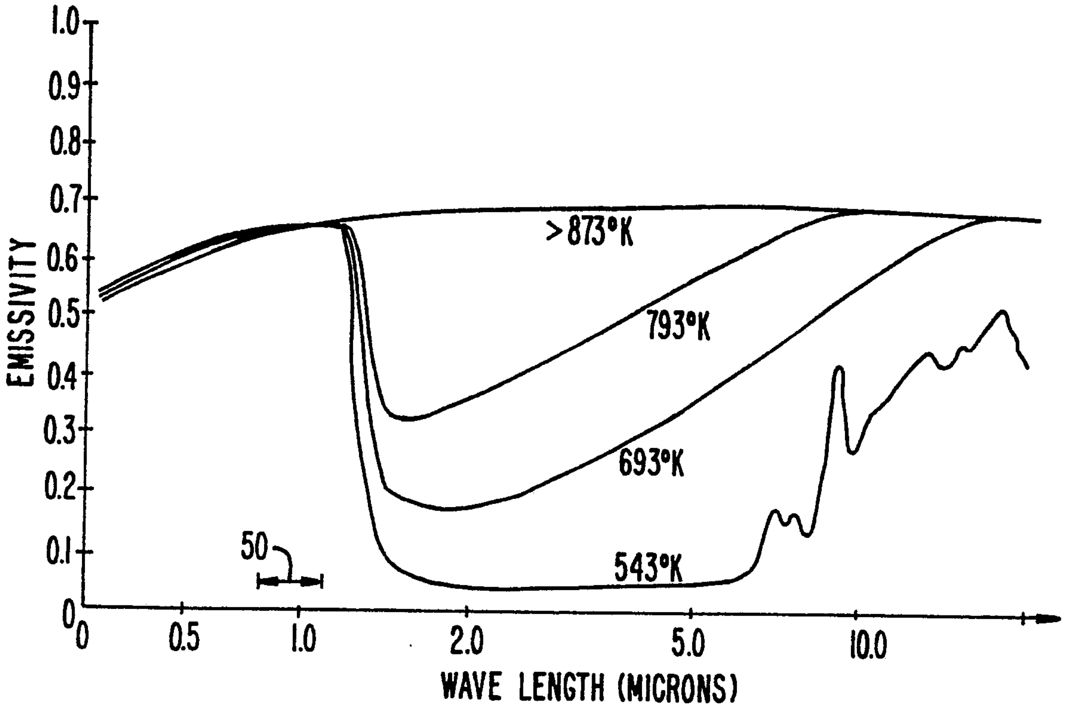

FIG. 2.

SUBSTITUTE SHEET

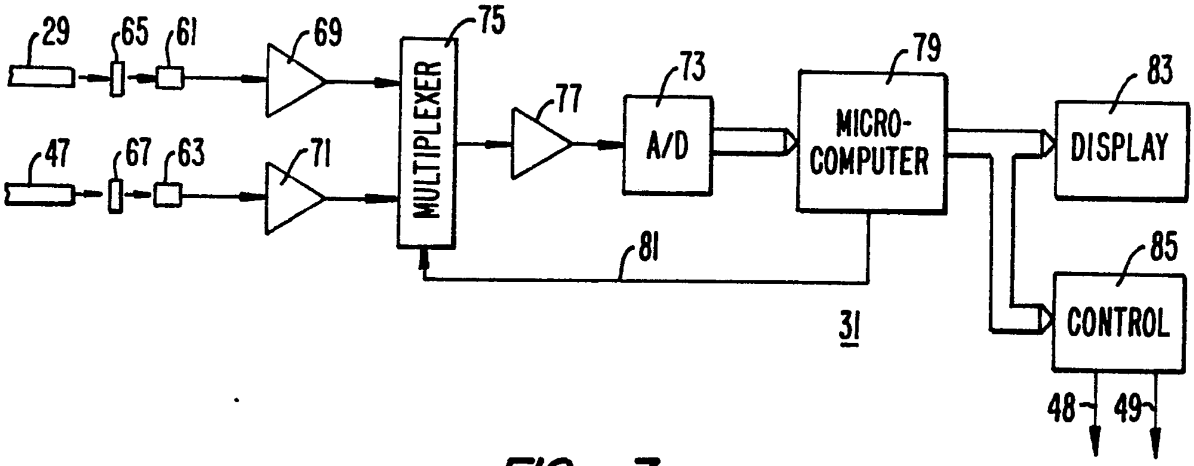
29
65
61
69
75
MULTIPLEXER
47
67
63
71
77
73
A/D
79
MICRO-
COMPUTER
83
DISPLAY
85
CONTROL
81
31
48
49

FIG. 3.

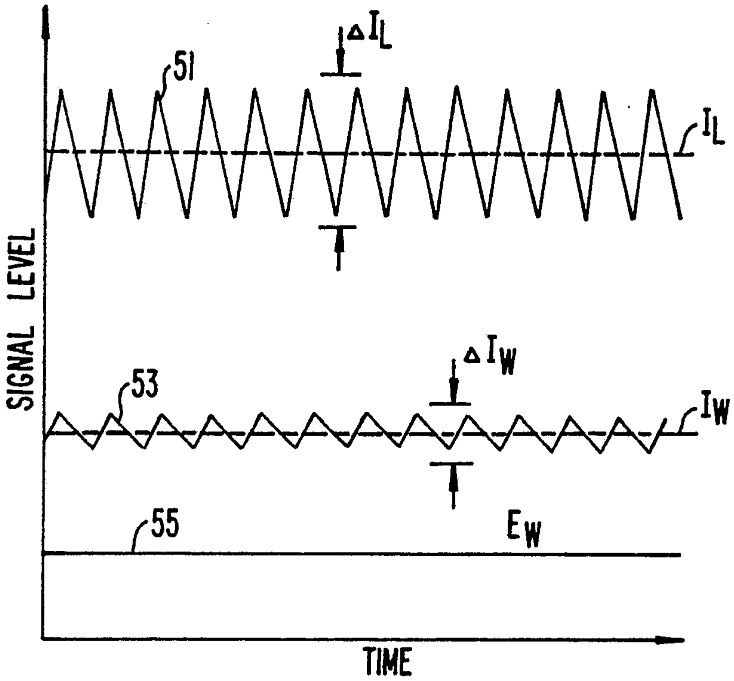
ΔI_L
51
I_L
SIGNAL LEVEL
ΔI_W
53
I_W
55
E_W
TIME

FIG. 4.

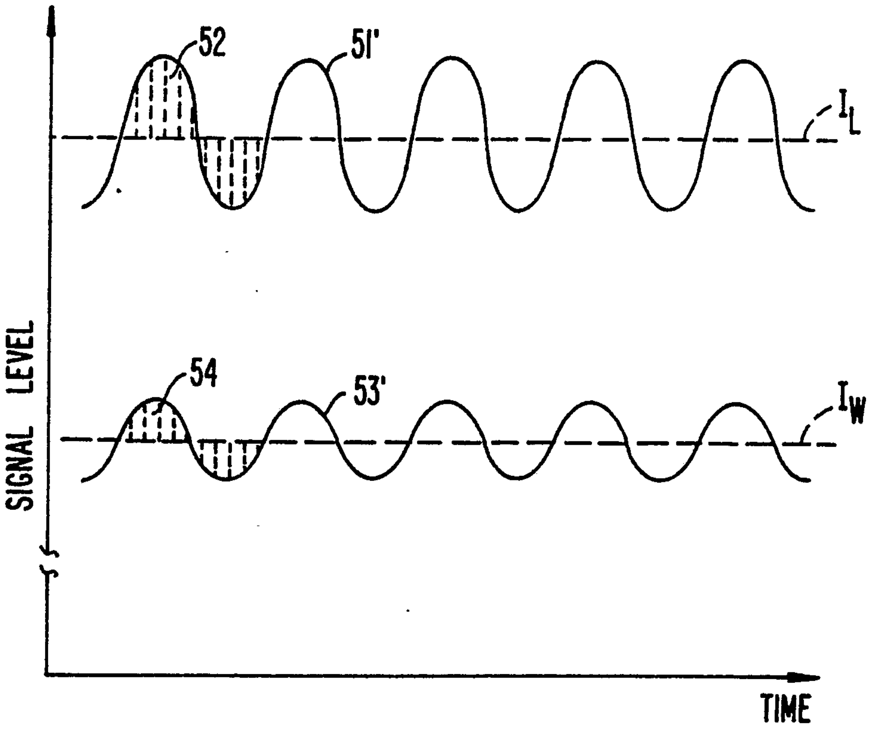

FIG. 5.

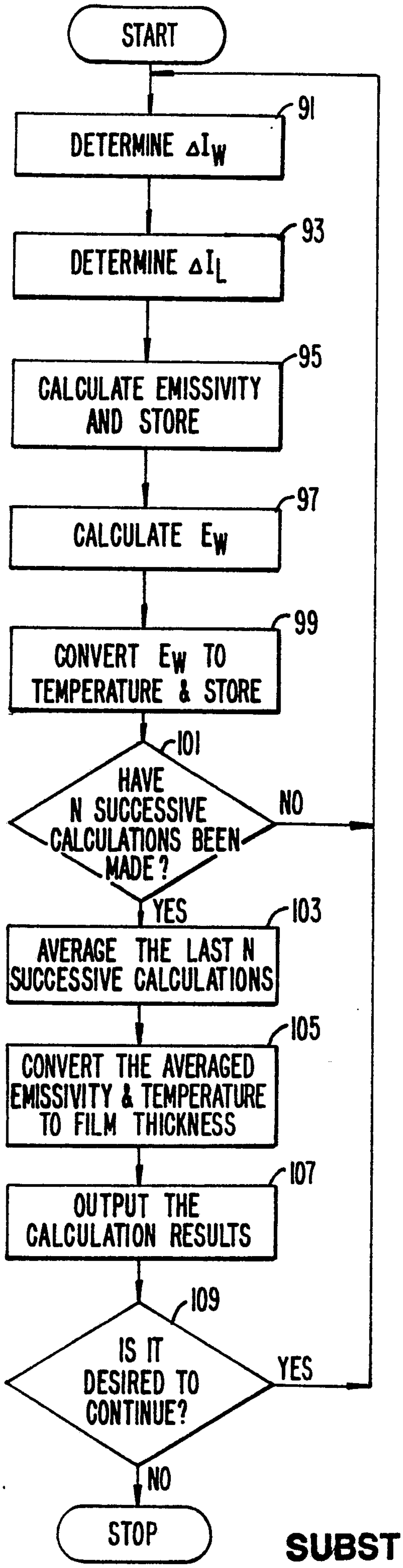
START
DETERMINE ΔI_W
91
DETERMINE ΔI_L
93
CALCULATE EMISSIVITY AND STORE
95
CALCULATE E_W
97
CONVERT E_W TO TEMPERATURE & STORE
99
HAVE N SUCCESSIVE CALCULATIONS BEEN MADE?
101
NO
YES
AVERAGE THE LAST N SUCCESSIVE CALCULATIONS
103
CONVERT THE AVERAGED EMISSIVITY & TEMPERATURE TO FILM THICKNESS
105
OUTPUT THE CALCULATION RESULTS
107
IS IT DESIRED TO CONTINUE?
109
YES
NO
STOP

FIG. 6.

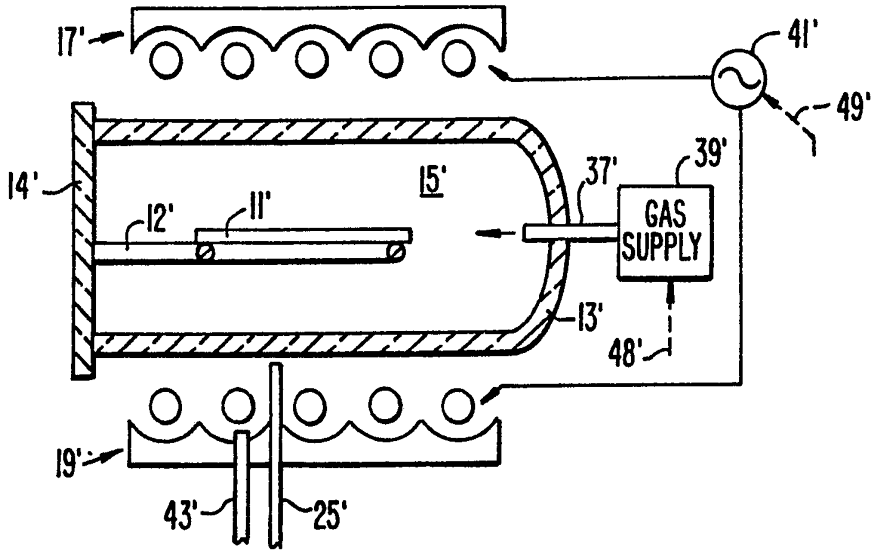
17'
41'
49'
39'
GAS SUPPLY
37'
15'
14'
12'
11'
13'
48'
19'
43'
25'

FIG. 7.

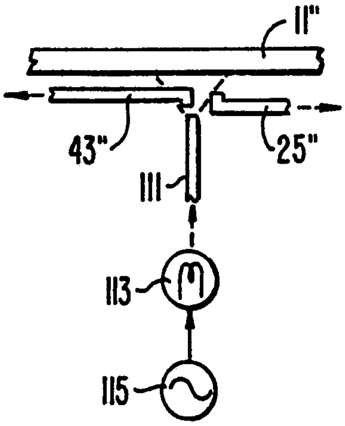
11"
43"
25"
111
113
115

FIG. 8.

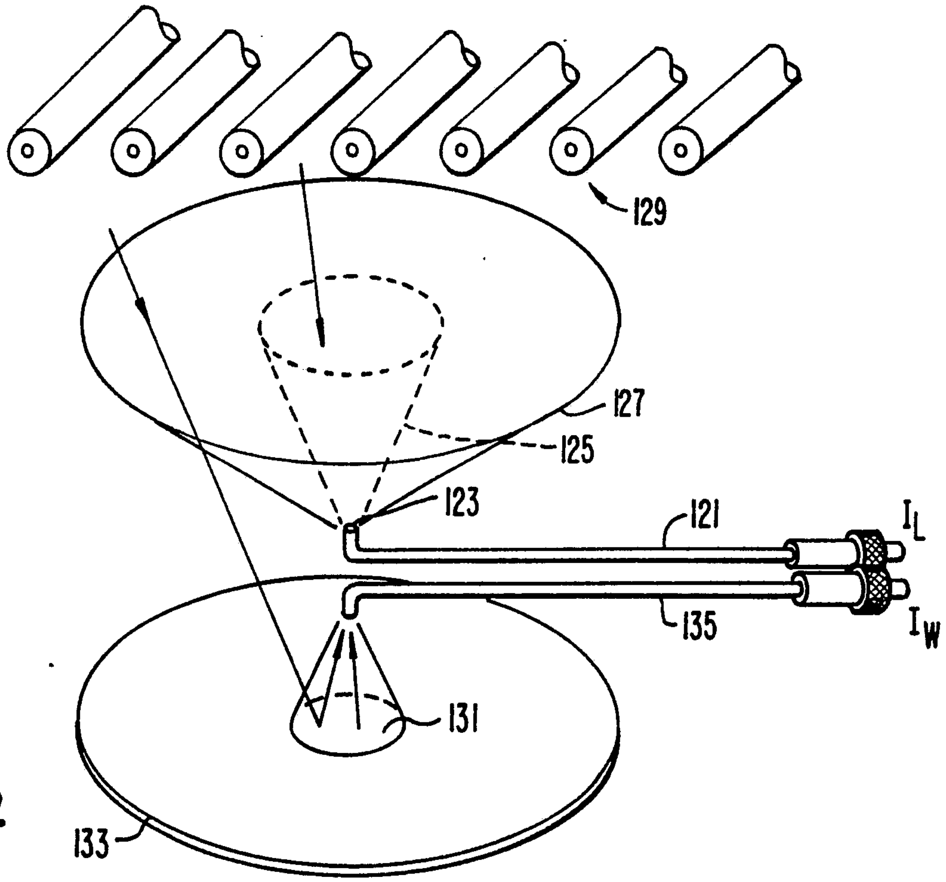

FIG. 9.

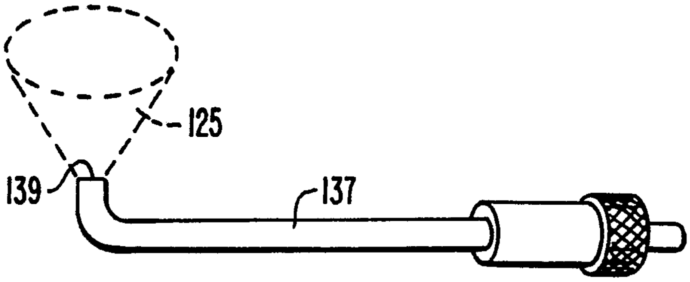

FIG. 10A.

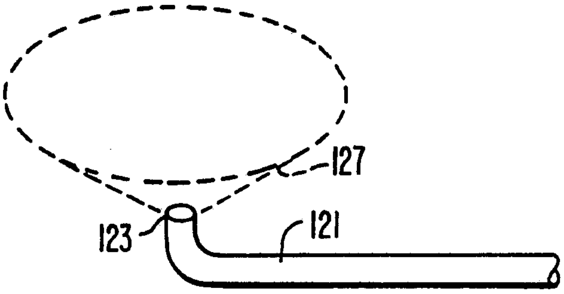

FIG. 10B.

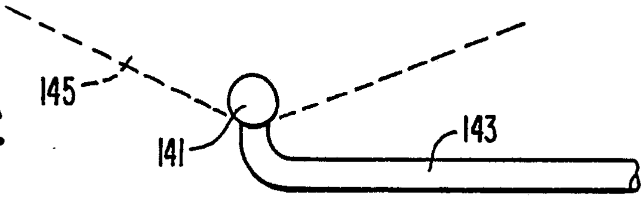

FIG. 10C.

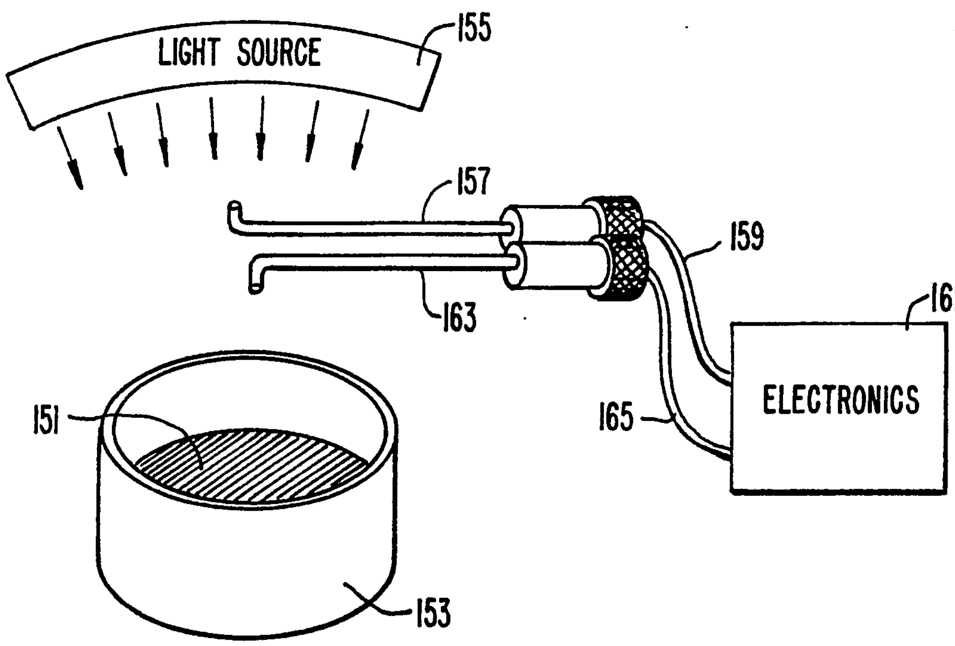
LIGHT SOURCE
155
157
159
161
163
ELECTRONICS
151
165
153

FIG. 11.

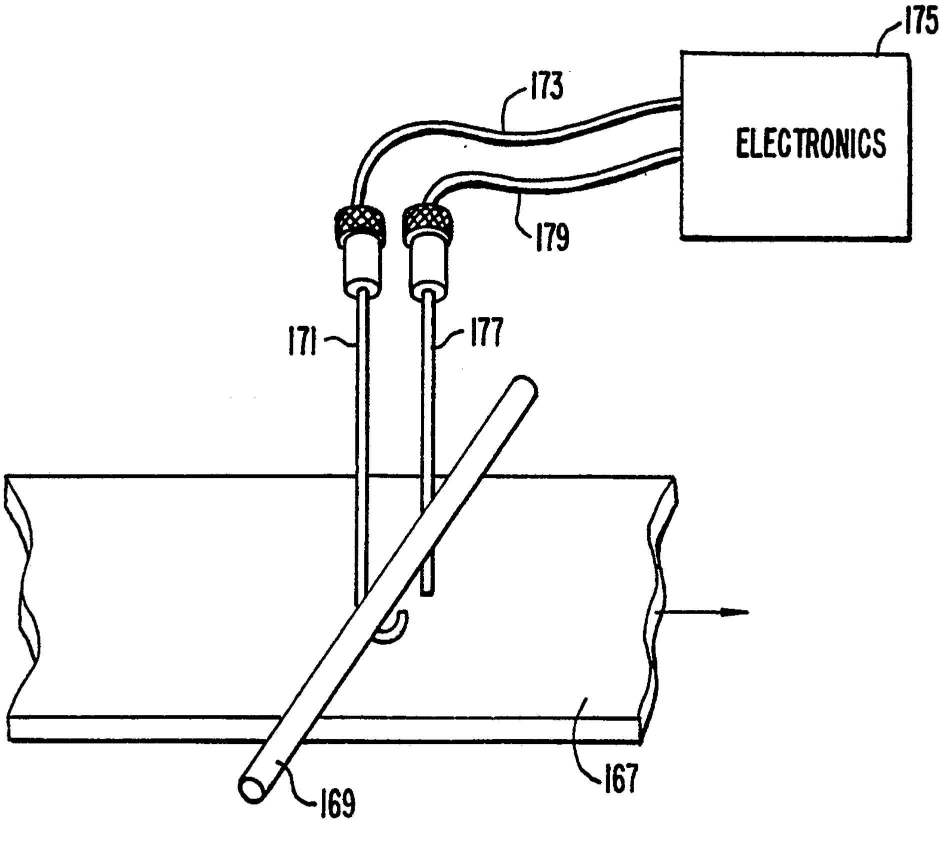
175
173
ELECTRONICS
179
171
177
169
167

FIG. 12.

INTERNATIONAL SEARCH REPORT

International Application No PCT/US 92/03456

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all)[6]

According to International Patent Classification (IPC) or to both National Classification and IPC

Int.Cl. 5 G01J5/00; G01B11/06

II. FIELDS SEARCHED

Minimum Documentation Searched[7]

Classification System	Classification Symbols
Int.Cl. 5	G01J ; G01N ; G01B

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched[8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT[9]

Category °	Citation of Document, [11] with indication, where appropriate, of the relevant passages [12]	Relevant to Claim No.[13]
Y	US,A,4 919 542 (NULMAN) 24 April 1990 see abstract see column 2, line 36 - column 4, line 28; figures	1,14-16
A		18,20,23
Y	EP,A,0 380 412 (MEASUREX) 1 August 1990 see abstract see page 6, line 39 - line 47 see page 7, line 16 - line 22; figure 2	1,14-16
A		18,20
A	PATENT ABSTRACTS OF JAPAN vol. 6, no. 129 (P-128)(1007) 15 July 1982 & JP,A,57 054 802 (JIYAPAN SENSAA CORPORATION) 1 April 1982 see abstract	1

-/--

° Special categories of cited documents : [10]

- "A" document defining the general state of the art which is not considered to be of particular relevance
- "E" earlier document but published on or after the international filing date
- "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- "O" document referring to an oral disclosure, use, exhibition or other means
- "P" document published prior to the international filing date but later than the priority date claimed
- "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step
- "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
- "&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search 27 AUGUST 1992	Date of Mailing of this International Search Report 04. 09. 92
International Searching Authority EUROPEAN PATENT OFFICE	Signature of Authorized Officer THOMAS R.M. R.M. Thomas

2

International Application No PCT/US 92/03456

III. DOCUMENTS CONSIDERED TO BE RELEVANT (CONTINUED FROM THE SECOND SHEET)		
Category °	Citation of Document, with indication, where appropriate, of the relevant passages	Relevant to Claim No.
A	PATENT ABSTRACTS OF JAPAN vol. 8, no. 113 (P-276)(1550) 26 May 1984 & JP,A,59 020 804 (MINOLTA CAMERA) 2 February 1984 see abstract ---	1,4,20, 21
A	EP,A,0 208 067 (HOESCH STAHL) 14 January 1987 see abstract see page 3, paragraph 3; figure ---	3,5,20, 24,26

ANNEX TO THE INTERNATIONAL SEARCH REPORT ON INTERNATIONAL PATENT APPLICATION NO. US 9203456 SA 59997

This annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report.
The members are as contained in the European Patent Office EDP file on 27/08/92
The European 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	Publication date	Patent family member(s)		Publication date
US-A-4919542	24-04-90	None		
EP-A-0380412	01-08-90	US-A-	4957770	18-09-90
		CA-A-	2007275	27-07-90
		JP-A-	2247528	03-10-90
EP-A-0208067	14-01-87	DE-A-	3521190	18-12-86
		AU-B-	592994	01-02-90
		AU-A-	5857986	18-12-86
		CA-A-	1274990	09-10-90
		JP-A-	62054011	09-03-87

For more details about this annex : see Official Journal of the European Patent Office, No. 12/82