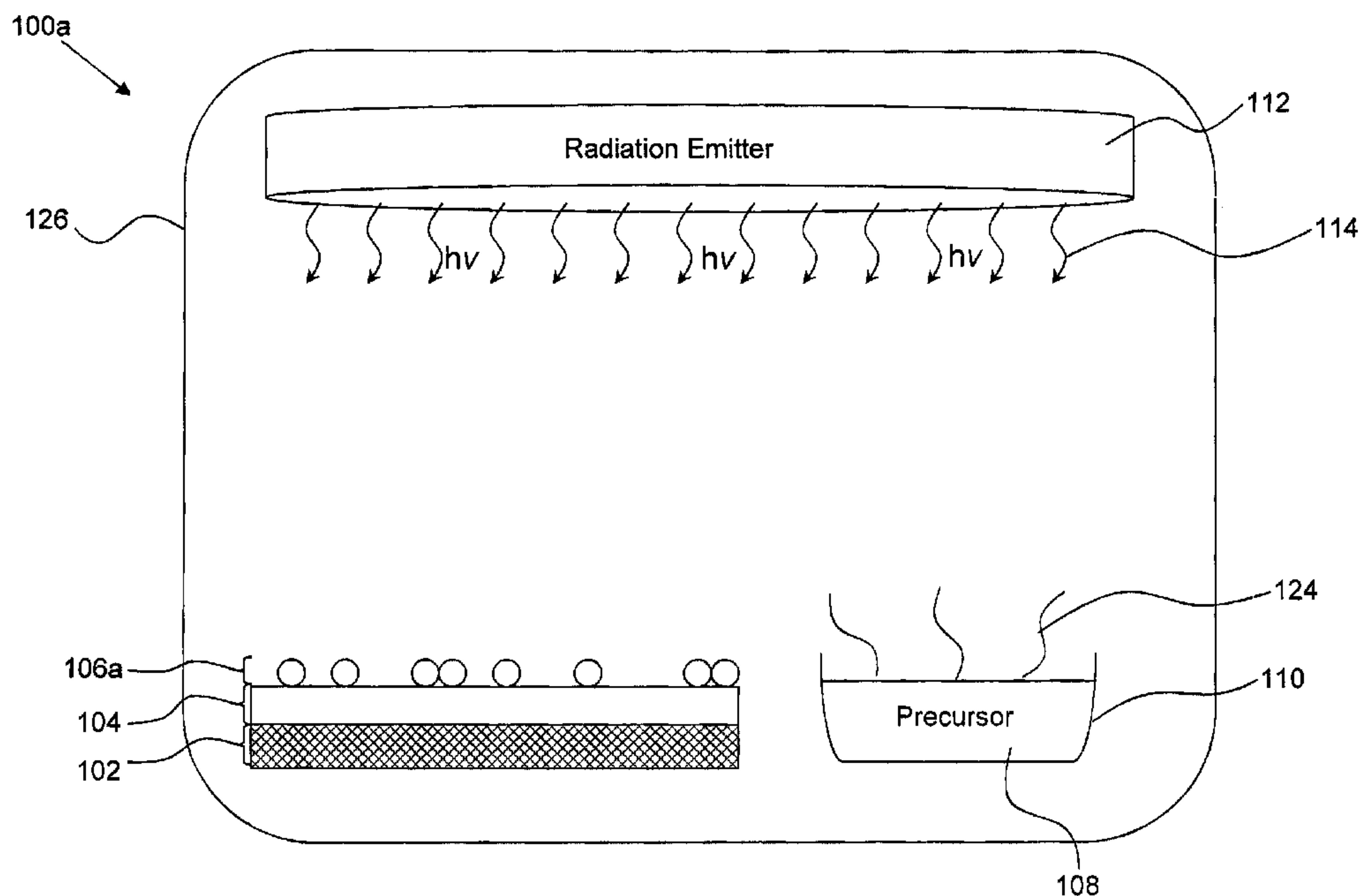




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(57) **Abrégé/Abstract:**

A method of increasing a work function of an electrode is provided. The method comprises obtaining an electronegative species from a precursor using electromagnetic radiation and reacting a surface of the electrode with the electronegative species. An electrode comprising a functionalized substrate is also provided.

ABSTRACT

A method of increasing a work function of an electrode is provided. The method comprises obtaining an electronegative species from a precursor using electromagnetic radiation and reacting a surface of the electrode with the electronegative species. An electrode comprising a functionalized substrate is also provided.

1 **FUNCTIONALIZATION OF A SUBSTRATE**

2 **TECHNICAL FIELD**

3 **[0001]** The following relates generally to functionalization of a substrate.

4 **BACKGROUND**

5 **[0002]** Organic light emitting diodes (OLEDs) are becoming more widely used in displays
6 and other optoelectronic applications. Organic electronic displays typically consist of a matrix of
7 OLEDs, each of which comprises thin films of organic materials that emit light when excited by
8 an electric current. The organic thin films are typically sandwiched between an anode and a
9 cathode, which provide an electric current to the organic thin film to enable the film to emit light.
10 In a display, the light emitted by the organic thin film must exit the thin film and penetrate
11 through at least one of the electrodes to be visible to a user. Hence, at least one of the
12 electrodes in the electrode pair comprises a transparent conductor such as a transparent
13 conducting oxide (TCO).

14 **[0003]** Indium tin oxide (ITO) is the most commonly used TCO due to its transparency and
15 its high conductivity relative to other TCOs. ITO is used in various applications requiring
16 transparency and conductivity including liquid crystal displays, plasma displays, photovoltaics,
17 electronic ink displays, and OLED displays. ITO is typically deposited as a thin film on a
18 transparent substrate such as glass.

19 **[0004]** In the context of OLEDs, an ITO layer is typically formed on a transparent substrate
20 used as the anode. Holes are injected from the anode into a hole transport layer (HTL), which
21 carries the holes to the light emitting thin film layer. Concurrently, electrons are injected via the
22 cathode and are transported through the electron transport layer (ETL) and recombine with the
23 holes in the light emitting thin film layer to release a photon. The photon emitted in the thin film
24 layer may then escape the thin film layer, pass through the HTL and exit the OLED device
25 through the ITO layer and the transparent substrate.

26 **[0005]** The energy required to inject holes from the anode is dependent on the hole injection
27 barrier height. The hole injection barrier height depends on the difference between the work
28 function of the anode and the highest occupied molecular orbital (HOMO) of the adjacent
29 organic layer. The hole injection barrier of existing OLEDs is high but this can be mitigated by
30 providing one or more intermediate organic layers. Each organic layer has a subsequently
31 deeper HOMO level, enabling holes to pass through a larger number of smaller injection

1 barriers rather than a single large injection barrier. However, each additional organic layer
2 increases the cost of the device and decreases the yield of the manufacturing process.

3 **[0006]** It is an object of the present invention to mitigate or obviate at least one of the above
4 disadvantages.

5 SUMMARY

6 **[0007]** In a first aspect, there is provided a method of increasing a work function of an
7 electrode comprising obtaining an electronegative species from a precursor using
8 electromagnetic radiation; and reacting a surface of the electrode with the electronegative
9 species.

10 **[0008]** The electronegative species may be a halogen. The electromagnetic radiation may
11 have a wavelength of at least about 100 nm. The electromagnetic radiation may have a
12 wavelength of less than about 400 nm. The method may further comprise cleaning the surface
13 of the electrode. The electrode may be a transparent conducting oxide. The transparent
14 conducting oxide may be ITO. The electronegative species may be selected to obtain an electrode
15 of a predetermined work function. The surface coverage of the species may be selected to
16 obtain an electrode of a predetermined work function. Up to about a monolayer of halogen may
17 be functionalized to the substrate. The halogen may be chlorine. The precursor may be a
18 volatile liquid. The precursor may be a gas. The substrate may be functionalized to increase its
19 stability in air.

20 **[0009]** In another aspect, an electrode comprising a substrate functionalized according to
21 the above method is provided. An organic electronic device comprising the electrode is also
22 provided.

23 **[0010]** In yet another aspect, there is provided the use of a system to chemically
24 functionalize a substrate with a species, the system comprising a reaction chamber; a radiation
25 emitter operable to emit electromagnetic radiation into the reaction chamber; wherein the
26 reaction chamber is operable to receive a precursor of the species and a substrate; and wherein
27 the electromagnetic radiation generates radicals from the precursor of the species to chemically
28 bond with the substrate. The radiation emitter may emit radiation having a wavelength of at
29 least about 100 nm. The radiation emitter may emit radiation having a wavelength of less than
30 about 400 nm. In an example embodiment, the radiation emitter is external to the reaction
31 chamber; and the reaction chamber is operable to at least partially transmit ultraviolet radiation
32 from the radiation emitter.

1 **[0011]** In yet another aspect, there is provided a method of increasing a work function of an
2 electrode comprising obtaining chlorine from a precursor using a plasma; and reacting a surface
3 of the electrode with the chlorine to form at least about 20% of a chlorine monolayer. In an
4 example embodiment, up to about a monolayer of chlorine may be reacted to the surface of the
5 electrode. The substrate may comprise a transparent conducting oxide. The transparent
6 conducting oxide may be ITO. The surface coverage of the chlorine may be selected to obtain
7 an electrode of a predetermined work function.

8 **[0012]** In yet another aspect, there is provided an electrode comprising a substrate
9 functionalized with at least about 20% of a monolayer of halogen. There is also provided an
10 organic electronic device comprising the electrode. The organic electronic device may comprise
11 an organic light emitting diode. The organic light emitting diode may be phosphorescent. The
12 organic light emitting diode may be fluorescent.

13 BRIEF DESCRIPTION OF THE DRAWINGS

14 **[0013]** Embodiments will now be described by way of example only with reference to the
15 appended drawings wherein:

16 **[0014]** FIG. 1 is a diagram illustrating a system in accordance with the present invention
17 comprising a substrate which is functionalized with approximately 0.5 of a monolayer of a
18 species;

19 **[0015]** FIG. 2 is a diagram illustrating a system in accordance with the present invention
20 wherein the substrate is functionalized with approximately 0.7 of a monolayer of the species;

21 **[0016]** FIG. 3 is a diagram illustrating a system in accordance with the present invention
22 wherein the substrate is functionalized with approximately one monolayer of the species;

23 **[0017]** FIG. 4 is an X-Ray photoelectron spectroscopy graph showing that the bonding state
24 of indium-chlorine bonds in InCl_3 is equivalent to the bonding state of indium-chlorine bonds in
25 chlorine-functionalized ITO;

26 **[0018]** FIG. 5 is an X-Ray photoelectron spectroscopy graph showing the relationship
27 between treatment time and chlorine functionalization of an ITO surface;

28 **[0019]** FIG. 6 is an energy level diagram illustrating the work function of an example ITO
29 electrode;

- 1 **[0020]** FIG. 7 is an energy level diagram illustrating the work function of an example
2 chlorine-functionalized ITO electrode;
- 3 **[0021]** FIG. 8 is a representative chart showing the relationship between the approximate
4 surface coverage of chlorine on an ITO substrate and the work function of the ITO substrate;
- 5 **[0022]** FIG. 9 is an X-ray photoelectron spectroscopy graph comparing the binding energy
6 of various halogen-functionalized substrates;
- 7 **[0023]** FIG. 10 is a representative chart contrasting the change in work function over time in
8 air for a chlorine functionalized ITO substrate and a bare ITO substrate;
- 9 **[0024]** FIG. 11 is a table showing the work function of various chlorinated and bare TCO
10 substrates after exposure to air;
- 11 **[0025]** FIG. 12 is a chart comparing the transmittance of chlorine-functionalized ITO on a
12 glass substrate to the transmittance of a bare ITO electrode on the same glass substrate;
- 13 **[0026]** FIG. 13 is a chart showing a spectrum of the ultraviolet radiation emitter;
- 14 **[0027]** FIG. 14 is an energy level diagram of an example phosphorescent green OLED
15 construction comprising a bare ITO anode;
- 16 **[0028]** FIG. 15 is an energy level diagram of an example phosphorescent green OLED
17 construction comprising a chlorinated ITO anode;
- 18 **[0029]** FIG. 16 is a representative chart showing the relationship between the work function
19 of a chlorine functionalized surface and the hole injection barrier height into a hole transport
20 layer;
- 21 **[0030]** FIG. 17 is an energy level diagram of an example phosphorescent green OLED
22 comprising a chlorine-functionalized anode;
- 23 **[0031]** FIG. 18 is a current-voltage chart showing a reduction in required driving voltage with
24 increasing surface chlorination of an ITO anode;
- 25 **[0032]** FIG. 19 is a chart showing the relationship between current efficiency and luminance
26 of the OLED of FIG. 17 comprising an anode with a monolayer of chlorine;
- 27 **[0033]** FIG. 20 is a diagram showing the efficiency of the OLED of FIG. 17 comprising a
28 monolayer of chlorine on the ITO anode;

- 1 **[0034]** FIG. 21 is a table comparing the efficiency of the OLED of FIG. 17 comprising a
2 monolayer of chlorine on the ITO anode to phosphorescent green OLED devices in the prior art;
- 3 **[0035]** FIG. 22 is a chart showing the change in luminance over time for an OLED
4 comprising a chlorine functionalized anode;
- 5 **[0036]** FIG. 23 is an energy level diagram of an example fluorescent green OLED;
- 6 **[0037]** FIG. 24 is a diagram showing the current-voltage characteristics of an example
7 fluorescent green OLED comprising a chlorine-functionalized ITO anode;
- 8 **[0038]** FIG. 25 is a diagram showing the efficiency of an example fluorescent green OLED
9 comprising a chlorine-functionalized ITO anode;
- 10 **[0039]** FIG. 26 is a chart showing the current density with respect to electric field for chlorine
11 functionalized ITO anode with respect to other anode types; and
- 12 **[0040]** FIG. 27 is a diagram illustrating a plasma functionalization apparatus in accordance
13 with the present invention.

14 DETAILED DESCRIPTION

15 **[0041]** It will be appreciated that for simplicity and clarity of illustration, where considered
16 appropriate, reference numerals may be repeated among the figures to indicate corresponding
17 or analogous elements. In addition, numerous specific details are set forth in order to provide a
18 thorough understanding of the example embodiments described herein. However, it will be
19 understood by those of ordinary skill in the art that the example embodiments described herein
20 may be practised without these specific details. In other instances, well-known methods,
21 procedures and components have not been described in detail so as not to obscure the
22 example embodiments described herein.

23 **[0042]** Also, the description is not to be considered as limiting the scope of the example
24 embodiments described herein. For example, reference is made to functionalizing a transparent
25 conducting oxide (TCO) substrate. It will be appreciated that other substrates may be
26 functionalized using the process described herein. Other non-transparent, or non-conducting
27 substrates may also be functionalized according to the process described herein.

28 **[0043]** Provided herein is a method of functionalization of a substrate with a species. In
29 particular, the functionalization of an electrode with an electronegative species to increase the
30 work function of the electrode is provided. Also provided is a method of functionalizing TCO

1 electrodes to achieve a higher work function without materially altering critical properties of the
2 TCO electrode such as conductivity and device stability. In one embodiment, the substrate is
3 functionalized using plasma disassociation of a precursor to release a reactive species, for
4 example, a halogen species. The halogen species is chemically reacted with a substrate to
5 increase the work function of the substrate.

6 **[0044]** Also provided is a substrate functionalized with up to about a monolayer of
7 electronegative species. The electronegative species may be a halogen. The halogen may be
8 chlorine. The substrate may be a TCO. An electrode comprising a functionalized substrate is
9 also provided. The substrate may be functionalized to increase the work function of the
10 electrode. In an example embodiment, the substrate is functionalized with at least about 20
11 percent of a monolayer. A functionalization of about 20 percent may be a significant
12 accomplishment. An organic electronic device employing an electrode comprising a
13 functionalized substrate is also provided.

14 **[0045]** It has now been found that transparent conducting oxides including indium tin oxide
15 (ITO), which may also be referred to as tin-doped indium oxide, may be directly used as an
16 electrode in an organic electronic device such as an organic light emitting diode (OLED). The
17 work function of ITO is approximately 4.7 eV in a vacuum. Because 4.7 eV rarely matches the
18 highest occupied molecular orbital (HOMO) level of many common hole transporting materials,
19 the use of ITO as an anode causes a high hole injection barrier and poor operational stability of
20 the device. It is well known that an anode having a work function that is closer in energy to the
21 HOMO level of the adjacent hole transporting organic material would reduce the hole injection
22 barrier, thereby reducing the required operating voltage and increasing the efficiency and
23 operation stability of organic electronic devices.

24 **[0046]** In the case of OLEDs, the active light emitting materials typically have HOMO levels
25 much greater than 4.7 eV. For example the HOMO level of tris(8-hydroxyquinolato)aluminium
26 (Alq_3), a fluorescent green light emitting compound, is 5.75 eV. Although some organic light
27 emitting materials may have HOMO levels closer to 4.7 eV, these materials are typically doped
28 into a host matrix that has a much higher HOMO level than 4.7 eV. Typically, holes must be
29 injected into the HOMO of the host in order for the dopant to emit light. For example, the HOMO
30 level of tris(2-phenylpyridine)iridium(III) [$\text{Ir}(\text{ppy})_3$], a phosphorescent green light emitting
31 compound is 5.4 eV, but is commonly doped into a 4,4'-bis(carbazol-9-yl)biphenyl (CBP) matrix.
32 CBP has a HOMO level of 6.1 eV, which is much greater than 4.7 eV. In particular, the HOMO
33 levels of the host materials used in phosphorescent OLEDs are about 6 eV or greater.

1 Therefore, there exists a need for a transparent electrode having a work function that is greater,
2 and preferably slightly greater, than the HOMO level of host materials used in OLEDs. In
3 particular, there exists a need for a transparent electrode having a work function of about 6 eV
4 or higher.

5 **[0047]** One way to increase the work function of a TCO substrate is to clean the surface of
6 the substrate to remove contaminants. For example, the surface of the TCO substrate may be
7 cleaned using ultraviolet (UV) ozone or O₂ plasma treatment. Plasma surface treatment and UV
8 ozone surface treatment are effective in removing organic contaminants and may leave
9 electronegative species on the surface of the TCO substrate. By way of example, UV ozone
10 cleaning of the surface of an ITO substrate may increase its work function to about 5.0 eV.
11 Cleaning the substrate may cause band bending at the surface of the substrate and an increase
12 in the surface dipole of the TCO due to electronegative oxygen species on the surface of the
13 substrate, thereby increasing the work function of the ITO substrate. Although reference is
14 made to cleaning the TCO substrate using UV ozone or O₂ plasma, the substrate may be
15 cleaned using liquid cleaning methods, for example, using a detergent or solvent.

16 **[0048]** It has been recognized that another way to raise the work function of ITO, which is
17 an important TCO substrate, is to chemically treat the ITO substrate with an electronegative
18 halogen, for example, fluorine. In the example of an ITO substrate, a halogen may be reacted
19 with indium atoms or tin atoms on the surface of the substrate to form up to an approximate
20 layer of indium halide. The process of reacting a surface of the TCO substrate with a halogen
21 may be referred to as "functionalization".

22 **[0049]** One way to chemically treat a TCO substrate with halogen is to react the surface of
23 the substrate with a halogen-containing acid (e.g. hydrochloric acid). A halogen gas may also
24 be dissolved in a carrier liquid to be applied to the surface of a TCO electrode. However, these
25 processes are difficult to control, may etch the surface of the substrate, and may leave very little
26 halogen functionalized to the surface of the substrate. Hence, the substrate surface may
27 become rougher, and more contaminated, while the work function of the electrode may not be
28 sufficiently increased. Furthermore, the conductivity and transparency of the substrate may be
29 reduced using this process. Halogenation of a substrate using an elemental hydrogen
30 containing solution (e.g. HCl) may be combined with UV ozone or O₂ plasma treatment.

31 **[0050]** The work function of a TCO substrate may also be increased using a halogen
32 containing plasma, which may cause a halide species to react with the surface of the TCO. For

1 example, a fluorocarbon plasma such as CFH_3 , an inorganic fluorine containing plasma such as
 2 SF_6 , or a pure halogen plasma such as F_2 may be used. Multiple plasma gasses may be used
 3 in combination. A carrier gas may also be used, for example, Ar, He, or N_2 .

4 **[0051]** Halogen-containing plasmas are typically used as standard reactive ion etching (RIE)
 5 industrial processes to dry etch substrates including TCO electrodes. Therefore, halogen-
 6 containing plasmas typically etch the surface of the substrate. This may decrease the
 7 conductivity of the surface and may contaminate the surface with halocarbons. Halocarbons
 8 are molecules comprising one or more carbon atoms covalently bonded to one or more halogen
 9 atoms (e.g. fluorine, chlorine, iodine, and bromine). The chemical bond between the
 10 contaminant and the substrate depends on the materials involved, type of plasma used and the
 11 processing conditions. The addition of an oxidant (e.g. O_2) may reduce the amount of deposited
 12 halocarbons and may also increase the rate at which the substrate is etched, negatively
 13 affecting other properties of the substrate. As is further described below, an example apparatus
 14 is provided for functionalizing species to the surface of a substrate while reducing the etching of
 15 the substrate.

16 **[0052]** It may be expected from the electronegativity of each of fluorine, chlorine, iodine, and
 17 bromine that fluorine functionalization provides the highest increase in work function since it has
 18 the highest electronegativity and therefore, would be expected to form the largest surface
 19 dipole. Surprisingly, it has now been found that chlorine functionalized TCO's have a yet higher
 20 work function. This has been confirmed from density functional theory calculations and
 21 experimental results as measured by X-ray photoelectron spectroscopy (XPS) using an ITO
 22 substrate that has been functionalized according to the process described herein. Table 1
 23 summarizes these results.

24 **Table 1: Experimental and Theoretical Work Function of Functionalized ITO**

Halogen Functionalized to ITO Surface	Experimental Work Function (XPS) [eV]	Density Functional Theory Calculation [eV]
fluorine	5.7	5.7
chlorine	6.1	6.1
bromine	5.4	-
iodine	5.2	-

25 **[0053]** Therefore, a chlorine-functionalized TCO may have a higher work function relative to
 26 TCO's functionalized with other halogens.

1 **[0054]** The above mentioned UV ozone and O₂ plasma cleaning treatments are reversible.
2 For example, the surface of the cleaned TCO substrate may be re-contaminated,
3 electronegative species on the surface of the TCO may desorb, and the surface of the substrate
4 is prone to hydrolysis. The above-described halogenation treatments offer greater stability than
5 the UV ozone or O₂ plasma treatments, however, typical application of these treatments are
6 prone to etching the surface of the TCO substrate. Furthermore, these halogenations
7 treatments may affect other critical properties including the surface roughness, conductivity and
8 transparency of the TCO. Also, handling halogen-containing gases for plasma processes
9 requires special safety precautions due to the toxicity and reactive nature of the materials
10 involved.

11 **[0055]** The above-mentioned techniques may be unable to increase the work function of
12 TCO substrates to a level enabling efficient injection of holes into hole transporting organic
13 materials with deep HOMO levels (e.g. 6 eV or greater). As a result, additional hole injection
14 layers (HILs) and hole transport layers (HTLs) with HOMO levels between the work function of
15 the TCO substrate and the HOMO level of the active organic layer are typically required in
16 practical organic optoelectronic devices to facilitate charge injection from the anode. For
17 example, a number of intermediate organic layers may be used, each having a subsequently
18 deeper HOMO level. This enables holes to pass through a larger number of smaller injection
19 barriers rather than a single large injection barrier. Each additional layer increases the cost of
20 the device and decreases the yield of the manufacturing process.

21 **[0056]** Other methods to incorporate a TCO electrode with an insufficiently high work
22 function into a device involve coating the TCO with a high work function polymer (e.g. PEDOT),
23 a self-assembled monolayer (SAM), or a metal oxide (e.g. WO₃). Such methods, however, may
24 increase impedance, device complexity and fabrication cost, while introducing additional
25 problems related to device stability.

26 **[0057]** The example embodiments described herein are, in one aspect, directed to the
27 functionalization of TCO thin films with halogens to modify their work function. In particular,
28 example embodiments are described with reference to halogens and/or halocarbons released
29 from a halogen-containing precursor compound under ultraviolet radiation. However, it can be
30 recognized that functionalization of other substrates using the methods described herein falls
31 within the scope of the invention. In one embodiment, the substrate is functionalized using
32 plasma dissociation of a precursor to release an electronegative species, for example, a
33 halogen. The halogen is chemically reacted with a substrate to increase the work function of

1 the substrate. For example, functionalizing a substrate with a halogen using a halogen-
2 containing plasma, and in particular, a chlorine-containing plasma, falls within the scope of the
3 invention, as is further described below.

4 **[0058]** In another embodiment, a method of functionalizing the surface of a substrate with a
5 species is provided, wherein a precursor containing the species is dissociated using
6 electromagnetic (EM) radiation. The species is then reacted with the substrate to increase the
7 work function of the substrate. In particular, a TCO substrate may be functionalized with a
8 halogen by dissociating the halogen atom from a precursor using EM radiation. Any wavelength
9 of electromagnetic radiation that breaks the bond between the species and the precursor may
10 be used, however, ultraviolet (UV) radiation, has been found to be particularly effective. In
11 particular, UV radiation having a wavelength of between 100 nm and 400 nm was found to be
12 effective. A catalyst may assist in breaking the bond between the halogen and the precursor.
13 The catalyst may comprise the chemical surface of the substrate.

14 **[0059]** The chemical bond between the species and the surface may increase the stability of
15 the functionalized material in air, as will be further described herein.

16 **[0060]** In some embodiments, and in examples that will be described herein, the halogen-
17 containing compound is a volatile halogen-containing organic precursor. It will be appreciated
18 that inorganic precursors may also be used. Organic precursors that release halogen atoms
19 include halocarbons. The precursor may comprise two different halogens, for example, fluorine
20 and chlorine.

21 **[0061]** Example precursors include, for example, haloalkanes, haloalkenes, and
22 haloaromatics. Common chlorinated precursors include chloromethane, dichloromethane
23 tetrachloromethane, perchloroethylene, tetrachloroethylene, 1,1,2,2-tetrachloroethane, 1,1,2-
24 trichloroethane, carbon tetrachloride, chloroform, methylene chloride, trichloroethylene, methyl
25 chloroform, 1,1,1-trichloroethane, 1,2,3-trichloropropane, ethylene dichloride, dichloropropane,
26 dichlorobenzene, trichlorobenzene, propylene dichloride, 1,2-dichloroethylene, 1,1
27 dichloroethane, etc. The precursor may comprise a halogen-containing polymer such as
28 polytetrafluoroethylene (PTFE).

29 **[0062]** Upon functionalizing the substrate, residual contamination may be removed by
30 additional treatment with EM radiation of an appropriate wavelength. Contaminants may be
31 removed using a UV ozone treatment and/or using an appropriate plasma cleaning treatment,
32 such as O₂ plasma. The cleaning process is performed at a low energy to reduce the likelihood

1 of the surface of the substrate being etched. When using an organic precursor, oxygen reacts
2 with the remnants of organic precursor molecules to form volatile molecules (e.g. CO₂ and H₂O)
3 which may be advantageously flushed from the surface of the substrate. Volatile molecules
4 may also evaporate from the surface of the substrate. Hence, in some embodiments, organic
5 precursors may leave less contamination in comparison with inorganic precursors after a
6 cleaning step.

7 **[0063]** However, inorganic precursors may be used in the methods described herein.
8 Examples of these precursors include pure halogen gases, hydrogen halides, boron halides,
9 sulphur halides, and phosphorus halides.

10 **[0064]** In some embodiments, the substrate may be functionalized with other elements, for
11 example, sulphur, boron, or phosphorus using appropriate volatile precursors. For example,
12 ammonium sulphide can be used to functionalize a substrate with sulphur. Other species that
13 may be functionalized to the surface of a substrate to alter the work function may be used.

14 **[0065]** The process of treating the substrate involves obtaining a transparent conducting
15 (TC) substrate, for example, an ITO film deposited on glass. Other example TCO substrates
16 include TCOs deposited on glass, such as tin oxide, indium oxide, cadmium oxide, FTO,
17 cadmium tin oxide (CTO), zinc tin oxide (ZTO), antimony tin oxide (ATO), aluminum zinc oxide
18 (AZO), titanium zinc oxide (TZO), gallium zinc oxide (GZO), aluminum gallium zinc oxide
19 (AGZO), indium gallium zinc oxide (IGZO), gallium indium oxide (GIO), zinc indium oxide (ZIO),
20 gallium indium tin oxide (GITO), zinc indium tin oxide (ZITO), titanium indium oxide (TIO), tin
21 cadmium oxide (TCO), indium cadmium oxide (ICO), zinc cadmium oxide (ZCO), aluminum
22 cadmium oxide (ACO). It will be appreciated that other transparent conducting (TC) substrates
23 may be used.

24 **[0066]** The TC substrate may be deposited on a transparent mechanical supporting layer,
25 for example, glass. The mechanical supporting layer may be rigid, flexible, planar, curved, or
26 any other geometry that may be functionalized using the method described herein.

27 **[0067]** The substrate may be comprised of a plurality of different layers. For example, the
28 substrate may comprise multiple layers of different TCOs, a metal film on top of a TCO, a metal
29 film sandwiched between two TCO layers, or a thin layer of a high work function material such
30 as a transition metal oxide on top of a metal or TCO layer. Various layers in the substrate may
31 be conducting, semiconducting, or insulating.

1 **[0068]** The substrate may comprise a plurality of layers of different metals, metal oxides,
2 TCO's, polymers and carbon based materials. The electrode may be a metal coated with a layer
3 of metal oxide, including its native metal oxide. The electrode may be solid or porous. One or
4 more layers of the substrate may comprise nano-material building blocks, for example nano-
5 particles, nano-rods, nano-tubes or other nano-scale materials. One or more layers of the
6 substrate may comprise a composite of different materials, for example nano-particles in a
7 polymer matrix. One or more layers of the substrate may comprise micron-scale particles.

8 **[0069]** The substrate may be patterned with nano-scale or micron-scale features, for
9 example, features to enhance the out-coupling of light from an optoelectronic device. One or
10 more layers of the substrate may be patterned. The substrate may be comprised of a plurality of
11 layers with different refractive index, for example to form a Bragg mirror or photonic crystal.

12 **[0070]** The substrate may be transparent, semi-transparent, opaque or reflective. The
13 substrate may include a mechanical support layer, such as a piece of glass, flexible plastic, or
14 semiconductor wafer. The substrate and mechanical support layer may be the same material.
15 The substrate may be mechanically self-supporting, for example a metal foil or silicon wafer.

16 **[0071]** Although reference is made to functionalizing a substrate with a halogen, it will be
17 appreciated that the substrate may be functionalized with other species. For example, the
18 substrate may be functionalized with a halocarbon to affect the surface energy of the
19 functionalized surface. Typically, halocarbon treatments erode the surface of TCO substrates
20 less than halogenations treatments, however, the equipment required to perform the halocarbon
21 treatments is specialized. Additionally, the conductivity of certain halocarbons is strongly
22 dependent on processing conditions, and therefore, difficult to control. Even with precise control
23 over processing conditions, the most conductive halocarbons, for example, conductive
24 fluorocarbons, are much less conductive than many TCO's including ITO. However, EM
25 dissociation of a halocarbon precursor to deposit a halocarbon film on a substrate may be
26 achieved, as is described below with reference to FIG 1.

27 **[0072]** Turning to FIG. 1, a system for functionalizing a substrate is provided. The system
28 may comprise a reaction chamber 126, in which a substrate 104 can be placed. A species may
29 be deposited on a substrate 104 in the reaction chamber 126. The precursor compound 108
30 can be placed, or fed into, the reaction chamber 126. The precursor compound 108 may be a
31 volatile liquid or solid. The dissociation of the precursor 108 may take place in the vapour
32 phase, liquid phase, or solid phase. A functionalization reaction with the surface of the

1 substrate 104 may take place on the surface of the substrate 104 in contact with the vapour
2 phase. The precursor compound 108 may also be a gas, in which case no evaporation of a
3 volatile precursor compound 108 is required to render the precursor compound 108 into the
4 vapour phase. A gas comprising the precursor compound 108 may be provided into the
5 reaction chamber 126 through a tube (not shown).

6 **[0073]** A radiation emitter 112 emits EM radiation into the chamber 126. The radiation
7 emitter 112 may emit UV radiation of, for example, between 100 nm and 400 nm. The radiation
8 emitter 112 may be located within the reaction chamber 126. The radiation emitter 126 may
9 alternately be external to the reaction chamber 126 if the walls of the reaction chamber are at
10 least partially transparent to the radiation.

11 **[0074]** In an example embodiment, the precursor 108 is applied directly to the surface of the
12 substrate 104, for example, in the form of a liquid or fine particulate (e.g. powder or
13 nanoparticulate). The dissociation reaction of the precursor compound 108 and the subsequent
14 functionalization of the substrate 104 reaction may proceed directly on the surface of the
15 substrate 104. The reaction may be catalyzed. For example, the reaction may be catalyzed by
16 the surface of the substrate 104. In an example embodiment, a catalyst is disposed in the
17 system to facilitate or enable the functionalization reaction.

18 **[0075]** Specifically, in the embodiment shown in FIG. 1, the precursor compound 108 is a
19 volatile liquid contained in an open reservoir 110. The precursor compound 108 evaporates into
20 its vapour phase.

21 **[0076]** The substrate 104 may itself be deposited on a mechanical supporting layer 102.
22 For example, the substrate may comprise a TCO thin film (e.g. ITO) deposited on a glass
23 substrate. The reaction chamber 126 isolates the substrate 104 from external contaminants
24 and retains the precursor vapour and the reactive species in the vicinity of the substrate 104.

25 **[0077]** The radiation emitter 112 is operable to emit EM radiation 114 into the reaction
26 chamber 126 to disassociate halogen species from the halogen-containing precursor 108. The
27 disassociation may be achieved in the vapour phase, in the liquid phase (i.e. in the reservoir
28 110 or on the surface of the walls of the reaction chamber 126), in the solid phase, or on the
29 surface of a substrate. An example halogen containing volatile precursor compound is
30 dihalobenzene.

31 **[0078]** As the halogen species chemically bonds with the substrate, a monolayer 106a
32 begins to form. As can be seen from FIG. 1, a partial monolayer 106a corresponding to

1 approximately half of the surface of the substrate 104 has been formed. As will be explained in
2 further detail below, the surface properties of the substrate 104 may be tuned based on the
3 surface coverage of the substrate 104 by the functionalizing species 106a.

4 **[0079]** As used herein, the term "monolayer" refers to a coating having approximately one
5 layer of atoms. It is understood that a layer having slightly more or less than a monolayer would
6 be considered a monolayer. It is also understood that a monolayer containing impurities, for
7 example residual carbon, would be considered a monolayer.

8 **[0080]** Although the system of FIG. 1 is described in terms of functionalizing a substrate
9 with a halogen, in some embodiments, the species being deposited is a halocarbon. The
10 halocarbon molecule may form a polymeric structure when functionalized to the surface of the
11 substrate. For example, a fluorocarbon film may be deposited on the surface of the substrate.
12 Fluorocarbon films comprising a C:F ratio controllably set between 1:3 and 3:1 have been
13 achieved and confirmed via X-ray photoelectron spectroscopy (XPS). Higher or lower ratios of
14 carbon to halogen are possible. XPS results have indicated the presence of CF_3 , CF_2 , CF , $C-$
15 CF , and $C-H$ bonds. Some species, for example, halocarbons may be able to react to form
16 multiple layers of a halocarbon film that may be several nanometres thick. The halocarbon film
17 may be conductive or may be insulating. The work function of the surface depends on the
18 amount and type of halocarbon.

19 **[0081]** Other properties may be changed, including surface energy, to increase or decrease
20 the hydrophobicity of the surface. A surface may be functionalized using a template to adjust
21 the surface energy at particular areas on the surface. A surface with a modified surface energy
22 may interact more favourably with certain species and resist interaction with other species. For
23 example, a hydrophobic surface would bead water while a hydrophilic surface could be wetted
24 with water. Functionalizing particular areas of a surface may enable the functionalized regions
25 to react with a species and the unfunctionalized regions to be resistant to reaction and vice-
26 versa. Although reference is made to about half a monolayer being formed on the substrate
27 104, less than a monolayer may be formed. For example, at least about 20 percent of a
28 monolayer may be formed on the substrate.

29 **[0082]** Turning now to FIG. 2, the system of FIG. 1 is shown, however, the partial monolayer
30 106a in FIG. 1 has become more populated with chemically bonded species, as is shown by
31 106b. The functionalization reaction may be controlled by varying the wavelength of the
32 electromagnetic radiation used to dissociate the halogen from the precursors, the intensity of

1 the EM radiation, the temperature at which the reaction takes place, the precursor being used,
2 the presence of any catalysts, the substrate, and the halogen being functionalized to the
3 substrate. The monolayer 106b continues to form on the substrate 104 as long as halogens
4 continue to react with the substrate 104.

5 **[0083]** Referring now to FIG. 3, the substrate 104 is shown with a monolayer 106c formed
6 on its surface. As described above, the monolayer 106c may have imperfections (not shown).
7 It may be desirable to cease the functionalization of the substrate 104 during the
8 functionalization process prior to forming a monolayer. The disassociation of precursors 116
9 may be ceased by removing, blocking, or otherwise interrupting radiation from the radiation
10 emitter 112. Once the release of halogen atoms from the precursors has ceased, the surface
11 coverage remains substantially constant. The ability to stop the functionalization reaction
12 almost instantaneously enables control over the degree to which the substrate 104 is
13 functionalized.

14 **[0084]** As is known, a functionalized substrate may include contaminants. Removing
15 organic contaminants from the surface may increase the work function of the substrate 104.
16 After functionalizing the desired portion of the substrate 104, the substrate 104 may be cleaned.
17 Specifically, the substrate 104 may be cleaned to remove contaminants deposited during the
18 functionalization reaction. For example, the contaminants may comprise organic compounds
19 originating from the precursor 108. In the case of organic precursors, the contaminants may be
20 reacted with UV generated ozone to produce volatile compounds which may be flushed from the
21 reaction chamber 126.

22 **[0085]** The functionalization process may not significantly increase the surface roughness of
23 the substrate 104. In an example embodiment, an ITO substrate was functionalized with
24 chlorine. An atomic force microscope (AFM) was used to characterize the surface of a bare UV
25 ozone treated ITO substrate and a chlorine-functionalized ITO substrate. The surface
26 roughness, expressed in terms of the arithmetic mean value, R_a , was found to be 2.2 nm for the
27 bare surface and 1.9 nm after being functionalized with a monolayer of chlorine atoms. It can
28 be appreciated that the monolayer was not a perfect monolayer and there may be some
29 variability in coverage and contamination.

30 **[0086]** Referring now to FIG. 4, an XPS chart showing the 2p core-level energy spectrum of
31 chlorine-functionalized ITO overlaid on the 2p core-level spectrum of an InCl_3 reference is
32 provided. The similarities between the InCl_3 curve and the chlorine-functionalized ITO curve

1 suggest that the indium-chlorine bonds on the surface of the functionalized ITO substrate are in
2 the same chemical state as the indium-chlorine bonds in InCl_3 .

3 **[0087]** Turning now to FIG. 5, a chart of the approximate surface functionalization (as
4 estimated by the 2p peak intensity of chlorine) with respect to reaction time is provided. Several
5 ITO substrates were functionalized with chlorine using the EM radiation dissociation method.
6 The duration of the functionalization reaction of each substrate was selected from between 0
7 and 10 minutes. XPS was used to measure the approximate surface coverage of chlorine on
8 the functionalized substrates. As the reaction time of the functionalization process increases
9 from 0 to 10 minutes, there is a proportional increase in the intensity of the 2p peak,
10 demonstrating that the functionalization of substrate can be increased by increasing the reaction
11 time. Conversely, with a shorter reaction time, the substrate is less functionalized, i.e., less than
12 a monolayer is formed on the surface of the substrate. By selecting an appropriate duration of
13 the functionalization reaction, the surface coverage may be tuned, for example, the surface
14 coverage may be tuned to a predetermined fraction of a monolayer.

15 **[0088]** FIG. 6 shows a band diagram of the work function of a standard ITO substrate with a
16 bare surface. The work function of bare ITO is approximately 4.7 eV (5 eV after cleaning),
17 which is significantly lower than the approximately 6 eV that is desired to efficiently inject holes
18 from the anode into the light emitting layer of typical organic electronic devices.

19 **[0089]** Turning now to FIG. 7, an energy level diagram is shown for an ITO substrate that
20 has been functionalized with a monolayer of chlorine is provided. Each chlorine atom in the
21 monolayer is chemically bonded to an indium atom in the ITO substrate, as was evidenced by
22 the XPS chart of FIG. 4, above. The work function at the surface of the functionalized ITO
23 electrode is significantly higher than the work function of bare UV ozone treated ITO. For
24 example, the work function of ITO functionalized with a monolayer of chlorine may be
25 approximately 6.1 eV in comparison with approximately ~5 eV for bare, UV ozone treated ITO.

26 **[0090]** The increase in work function of the chlorinated substrate with respect to the bare
27 substrate may be attributable to the surface dipole induced by the chlorine atoms on the surface
28 of the ITO. Therefore, functionalizing species increase the work function of the ITO in
29 proportion to their dipole moment with the surface of the substrate. A desired increase in the
30 work function of an electrode can be obtained by selecting an appropriate functionalization
31 species. Surprisingly, as was described above, chlorine achieves the highest dipole despite
32 being less electronegative than fluorine. Density functional theory calculations indicate that the

1 In-Cl bond length is greater than the In-F bond length, resulting in a larger net dipole moment for
2 chlorine in comparison with fluorine.

3 **[0091]** The work function of the TCO substrate may be tuned within a range by controlling
4 the reaction time, for example, by interrupting or blocking radiation 114 from the radiation
5 emitter 112. The concentration of the precursor compound may also be selected to tune the
6 range. For example, by depositing less than a monolayer on the surface of a substrate, the
7 work function may be set to be lower than the work function of a substrate that has been
8 functionalized with a full monolayer of species but higher than that of a bare substrate surface.

9 **[0092]** Referring to FIG. 8, a chart illustrating the relationship between work function and
10 surface coverage of chlorine on an ITO substrate as approximated from the chlorine 2p core-
11 level XPS results is provided. The work function is approximately linearly related to the surface
12 functionalization of the ITO substrate. It will be appreciated that the chart of FIG. 8 is a rough
13 approximation and is a representation of the relationship only.

14 **[0093]** By way of example, a functionalization of about 15% of a monolayer corresponds to
15 a work function of approximately 5.65 eV. A functionalization of approximately 95% of a
16 monolayer corresponds to a work function of approximately 6.15 eV. Hence, the work function
17 may be tuned depending on the application by functionalizing the surface with up to a
18 monolayer. When a higher work function is desired, for example, above 6.1 eV, the surface
19 may be functionalized with about a monolayer of chlorine. As stated above, it will be
20 appreciated that the monolayer, or portions of the monolayer, may be imperfect.

21 **[0094]** In the context of OLEDs, ITO is commonly used as an anode. The work function of a
22 functionalized ITO anode may be tuned to match the HOMO level of the organic hole
23 transporting material, as is further described below.

24 **[0095]** Referring to FIG. 9, XPS core-level spectra of ITO functionalized with iodine,
25 bromine, and fluorine are provided. As was described above, chlorine induces the largest
26 dipoles in the halogen-indium bond on a functionalized ITO surface, thereby providing the
27 maximum increase in work function relative to ITO functionalized with other halogens.

28 **[0096]** As can be seen in Table 1 below, the functionalization of various TCO surfaces is
29 possible. UPS refers to ultraviolet photoelectron spectroscopy.

1
2
3**Table 2: Experimental work function from XPS/UPS of Various Functionalized Substrates**

Substrate	Functionalized Species	Work Function of Clean Substrate [eV]	Work Function of Functionalized Substrate [eV]
ITO	chlorine	4.7	6.1
FTO	fluorine	4.9	5.6
ZnO	chlorine	4.7	5.3
Au	chlorine	5.2	6.2

4

5 **[0097]** In addition to increasing the work function of the electrode, halogen functionalization
6 increases the stability of the work function of the electrode relative to that of a bare UV ozone or
7 O₂ plasma treated TCO electrode. Turning to FIG. 10, a chart showing the stability of the work
8 function of an ITO substrate functionalized with a monolayer of chlorine is compared with a bare
9 ITO substrate in the presence of air. The surface of the bare substrate was treated with UV
10 ozone for 15 minutes. As can be seen from Fig. 10, the work function of the bare electrode
11 drops by approximately 0.1 eV over about three hours in the presence of air. In contrast, there
12 is no substantial change in the work function of the functionalized substrate. This demonstrates
13 the increased stability provided to functionalized substrates. This may be advantageous in a
14 production environment, as a functionalized substrate may be left in atmospheric conditions for
15 a period of time without impacting the work function of the substrate. Higher stability may
16 enable substrates to be stored in air, rather than in a vacuum or under an inert gas. The
17 stability of the functionalized substrate depends on the ambient environment including the
18 ambient temperature and humidity.

19 **[0098]** Turning to FIG. 11, a table is provided showing the work function of various other
20 transparent conducting oxides after being exposed to air for a period. It can be appreciated that
21 under the same conditions and after exposure to air, the work function of the functionalized
22 substrate is substantially higher than the work function of the bare substrate under the same
23 conditions.

24 **[0099]** Referring now to FIG. 12, a chart is provided to illustrate that the transmittance
25 characteristics of a chlorine-functionalized ITO substrate are not substantially inferior to the
26 transmittance characteristics of a bare ITO substrate. The ITO layers were deposited on
27 transparent substrates. As can be seen from the chart, the transmittance curves are very

1 similar over a wide range of wavelengths. Importantly, the curves are almost indistinguishable
2 over the visible spectrum, illustrating that a chlorine-functionalized ITO anode may be used in
3 an organic optoelectronic device with no increase in the attenuation of light transmitted through
4 the anode relative to that of a bare ITO anode.

5 **[00100]** Turning to FIG. 13, a spectrum of the ultraviolet lamp used to functionalize the ITO
6 substrates in the examples above is provided. Specifically, the spectrum corresponds to that of
7 a PL16-110 Photo Surface Processing Chamber (Sen Lights™). The wavelength
8 corresponding to the cut-off wavelength of Pyrex™ glass, which may be used as a reaction
9 chamber is also provided.

10 **[00101]** The conductivity of a chlorine-functionalized ITO substrate is also not substantially
11 inferior to the conductivity of a bare ITO substrate. As measured with a 4-point probe the sheet
12 resistance of an example chlorine-functionalized ITO substrate is 18.2 Ohms per square,
13 compared to 18.1 Ohms per square for a bare ITO substrate.

14 **[00102]** One application of a transparent conducting substrate, for example, an ITO substrate
15 that has been functionalized to have a high work function, is the use of the substrate in an
16 organic electronic device. Functionalizing the surface of an ITO substrate with a halogen
17 species to increase the work function of the ITO substrate can reduce the hole injection barrier.
18 Reducing the hole injection barrier improves the efficiency of hole injection in an OLED, thereby
19 decreasing the amount of voltage required to induce a current in the device.

20 **[00103]** It will be appreciated that although a functionalized TCO substrate is shown in an
21 example OLED construction, other OLED constructions may use functionalized TCO substrates.
22 Furthermore, other types of electronic devices may comprise functionalized TCO substrates.

23 **[00104]** FIG. 14 shows an example energy diagram of an embodiment of an OLED using a
24 transparent conducting substrate from the prior art. An ITO layer 1280 is typically formed on a
25 transparent substrate used as the anode. Holes are injected from the anode 1280 into a hole
26 injection layer (HIL) 1282, then to a hole transport layer (HTL) 1284, through an electron
27 blocking layer (EBL) 1286 and into to the light emitting thin film layer 1292. Concurrently,
28 electrons are injected via the cathode 1298 and are transported through the electron transport
29 layer (ETL) 1296, through the hole blocking layer (HBL) 1294, and recombine with holes in the
30 light emitting thin film layer to release photons. The photons emitted in the thin film layer may
31 then escape through ITO layer 1280 and any transparent substrate supporting the ITO layer

1 1280. A ghost line 1290 is provided to show the relative work function of a chlorine-
2 functionalized ITO layer, which is significantly better aligned with the emitting layer.

3 **[00105]** FIG. 15 is an energy level diagram for a simplified phosphorescent OLED comprising
4 a chlorine functionalized ITO electrode 1380. At lower barrier heights, holes can be injected
5 more efficiently from the anode. As can be seen from the diagram, the height of the hole
6 injection barrier, which is dependent on the difference between the HOMO of the emitting layer
7 and the work function of the ITO electrode 1380, is relatively low for the chlorine functionalized
8 electrode. This lower hole injection barrier enables the electrode to inject directly into the host
9 1284, thereby enabling the host and the HTL 1283 to be the same material. Since the chlorine-
10 functionalized anode is closely aligned with the HOMO level of the HTL 1283, there is no need
11 for the HIL layer 1282. In contrast, a bare ITO electrode 1280 has a high injection barrier,
12 making it inefficient to inject holes without the intermediate HIL, as was shown in FIG. 14. If the
13 HTL and ETL are selected to have appropriate energy levels, as understood by one skilled in
14 the art, the EBL and HBL may also be eliminated.

15 **[00106]** Referring now to FIG. 16, a UPS chart showing the relationship between the work
16 function of the anode and the barrier height for holes in an OLED device is provided. It can be
17 seen that increasing the work function of the electrode using halogen functionalization reduces
18 the hole injection barrier height.

19 **[00107]** In an example embodiment, a chlorine-functionalized ITO anode was prepared for
20 use in a phosphorescent green bottom emitting OLED. An OLED comprising a chlorine-
21 functionalized ITO anode and another OLED comprising a bare UV ozone treated ITO anode
22 were fabricated in a Kurt J. Lesker LUMINOS™ cluster tool with a base pressure of 10^{-8} Torr on
23 commercially patterned ITO coated glass (25 mm × 25 mm). ITO substrates were ultrasonically
24 cleaned with a standard regiment of Alconox™ dissolved in deionized (DI) water, DI water,
25 acetone, and methanol. The ITO substrates were then treated using UV ozone treatment for 3
26 minutes in a PL16-110 Photo Surface Processing Chamber (Sen Lights).

27 **[00108]** Chlorine-functionalized ITO was prepared by functionalizing the surface of the ITO
28 substrate for 10 minutes according to the method described in FIG. 1 and in a Pyrex™ Petri dish
29 with 0.2 ml 1,2-dichlorobenzene as the precursor compound. A Pyrex™ reservoir was used as
30 the chamber and the UV source was located outside of the chamber. A transmission spectrum
31 of Pyrex™ is provided in FIG. 24a and the spectrum of the UV lamp is provided in FIG. 24b.

1 Once the functionalization reaction was complete, the ITO substrate was treated in UV ozone
2 for 3 minutes.

3 **[00109]** The organic layers and the LiF cathode were thermally deposited from alumina
4 crucibles in dedicated organic chamber. The Al layer was deposited in a separate dedicated
5 metal deposition chamber from a boron nitride crucible without breaking vacuum. All layers were
6 patterned using stainless steel shadow masks to define the device structure. The active area for
7 all devices was 2 mm².

8 **[00110]** The standard device structure is as follows: anode/CBP (35 nm)/CBP:Ir(ppy)₂(acac)
9 (15 nm, 8%)/TPBi (65 nm)/LiF (1 nm)/Al (100 nm), where Ir(ppy)₂(acac) is bis(2-phenylpyridine)
10 (acetylacetonate)iridium(III), and TPBi is 2,2',2''-(1,3,5-benzinetriyl)-tris(1-phenyl-1-H-
11 benzimidazole).

12 **[00111]** An energy level diagram 1200 of the example phosphorescent OLED structure is
13 provided in FIG. 17. The chlorine-functionalized ITO anode 1202 has a significantly higher work
14 function than a bare UV ozone treated ITO anode 1206. Hence, the chlorine-functionalized
15 anode is better able to inject holes into the CBP layer 1204, as the HOMO level of the CBP
16 layer 1204 is well aligned with the work function of the chlorine-functionalized ITO anode. The
17 Ir(ppy)₂(acac) layer 1208 may be doped into the CBP layer 1204. The TPBi layer 1210 is in
18 electrical communication with the LiF/Al cathode layer 1212 and the Ir(ppy)₂(acac) layer 1208.

19 **[00112]** FIG. 18 is a diagram showing the current-voltage characteristics of the example
20 device of FIG. 17. As can be seen, as the treatment time increases to a point where a
21 monolayer is formed, the voltage required to drive current decreases. Hence, if a monolayer of
22 chlorine is functionalized to the surface of the ITO anode used in the example OLED device, the
23 voltage required to operate the OLED may be significantly reduced. As can be seen from FIG.
24 18, the voltage may be reduced by approximately 4V at an equivalent current density.

25 **[00113]** FIG. 19 is a chart of the current efficiency of the example OLED device of FIG. 17
26 comprising a chlorine-functionalized anode with respect to the luminance being output from an
27 OLED reference device from the prior art. Specifically, the OLED device comprises a UV ozone
28 treated anode with the structure: anode/PEDOT:PSS (5 nm)/ α -NPD (35 nm)/CBP:Ir(ppy)₂(acac)
29 (15 nm, 8%)/TPBi (65 nm)/LiF (1 nm)/Al (100 nm), where α -NPD is N, N'-bis(naphthalen-1-yl)-
30 N,N'-bis(phenyl)-benzidine. It will be appreciated that the PEDOT:PSS (5 nm)/ α -NPD (35 nm)
31 layers in the reference device are required to inject holes into the CBP:Ir(ppy)₂(acac) emission
32 layer from the bare UV ozone treated ITO anode. It can be seen from FIG. 19 that the chlorine-

1 functionalized anode increases the current efficiency with respect to the reference OLED
2 comprising a bare UV ozone treated electrode. In particular, at high luminance, the OLED
3 comprising the functionalized anode is significantly more efficient.

4 **[00114]** Turning to FIG. 20, the current efficiency and external quantum efficiency (EQE) of
5 the phosphorescent OLEDs comprising a chlorine functionalized anode is provided. The
6 phosphorescent OLED has a high maximum current efficiency of 93.5 cd/A at 400 cd/m², which
7 corresponds to a maximum EQE of 24.7%. At 10,000 cd/m² the current efficiency and EQE are
8 still relatively high at 79.6 cd/A and 21% respectively. Turning to FIG. 21, the example OLED of
9 FIG. 17 comprising a chlorinated ITO anode is compared with devices constructed using
10 methods found in the prior art. As can be seen, the OLED comprising the chlorine-
11 functionalized anode may be constructed to be significantly more simple in terms of device
12 layers and materials and may further exhibit a significantly higher external quantum efficiency.

13 **[00115]** Referring now to FIG. 22, a chart is provided showing the change in luminance
14 measured in vacuum for the example OLED with the structure: electrode/CuPc (25nm)/ α -NPD
15 (45 nm)/CBP:Ir(ppy)₂(acac) (15 nm, 8%)/TPBi (10 nm)/Alq₃ (45 nm)/LiF (1 nm)/Al (100 nm),
16 where CuPc is copper phthalocyanine. As can be seen, the luminance of an OLED comprising
17 an ITO anode that has been functionalized with chlorine is higher than an OLED comprising a
18 bare UV ozone treated ITO anode after being in operation for several hours. This demonstrates
19 that the OLED comprising an ITO anode maintains a relatively higher luminance over time.

20 **[00116]** In another example embodiment, a fluorescent green OLED was fabricated following
21 the same procedure as for the phosphorescent OLED outlined above. The standard device
22 structure of the OLED is as follows: anode/CBP (50 nm)/Alq₃:C545T (30 nm, 1%)/Alq₃ (15
23 nm)/LiF (1 nm)/Al (100 nm), where CBP is 4,4'-bis(carbazol-9-yl)biphenyl, Alq₃ is tris(8-hydroxy-
24 quinolinato)aluminium, and C545T is 2,3,6,7-tetrahydro-1,1,7,7,-tetramethyl-1H, 5H,11H-10-(2-
25 benzothiazolyl)quinolizino[9,9a,1gh]coumarin.

26 **[00117]** An energy level diagram 900 of the fluorescent OLED structure is provided in FIG.
27 23. Numeral 902 refers to the chlorine-functionalized ITO anode, which has a significantly
28 higher work function than the bare ITO anode 906. Hence, the chlorine-functionalized anode
29 902 is better able to inject holes into the CBP 904, as the HOMO level of the CBP 904 is well
30 aligned with the work function of the chlorine functionalized ITO anode 902. The OLED further
31 comprises an Alq₃:C545T layer 908 and an Alq₃ layer 910, which is in communication with the
32 LiF/Al cathode 912.

1 **[00118]** The HOMO level of the CBP layer layer in contact with the anode is approximately
2 6.1 eV. The work function of the functionalized anode is approximately 6.1 eV and the work
3 function of the bare anode is approximately 5.0 eV, after being treated with ozone, as measured
4 by ultraviolet photoelectron spectroscopy (UPS). The work function of the bare anode is too low
5 to efficiently inject holes into the OLED whereas the work function of the functionalized anode is
6 more aligned with the HOMO level of the CBP layer.

7 **[00119]** FIG. 24 is a chart showing the current-voltage characteristics of a fluorescent green
8 OLED comprising a chlorine-functionalized ITO anode with respect to a fluorescent green OLED
9 of identical construction comprising a bare UV ozone treated ITO anode. As can be seen from
10 FIG. 24, the voltage required to achieve a particular current density is significantly lower for the
11 OLED comprising the chlorine-functionalized anode.

12 **[00120]** Specifically, the current density of the OLED device comprising the functionalized
13 electrode dramatically increases with a driving voltage of more than 6 volts. At 10 volts, the
14 current density of the OLED comprising the chlorine-functionalized ITO anode is approximately
15 300 mA/cm². In contrast, the current density of the OLED comprising the bare ITO electrode is
16 insignificant. The higher current density of the OLED comprising the chlorine-functionalized ITO
17 anode demonstrates that the higher work function enables more efficient injection of holes into
18 organic hole transporting materials with deep HOMO levels.

19 **[00121]** A major advantage of aligning the work function of the ITO anode with the HOMO of
20 the CBP layer is that the power efficiency of the OLED is increased; that is to say, the light
21 output per unit of electrical input is increased. Referring to FIG. 25, a chart showing the current
22 and power efficiencies of the OLED devices discussed above is provided. The device with bare
23 ITO anode has a lower power efficiency and a lower current efficiency due to the poor injection
24 of holes from bare ITO anode into the deep 6.1 eV HOMO of CBP. The device with chlorine-
25 functionalized ITO anode has a much higher efficiency, with a maximum current efficiency at a
26 luminance of approximately 1000 cd/m² of 23 cd/A versus the approximately 18cd/A for the bare
27 ITO anode.

28 **[00122]** Similarly, the power efficiency of the OLED comprising a chlorine-functionalized ITO
29 anode is approximately 12 lm/W at a luminance of 1000 cd/m², whereas the power efficiency of
30 the OLED comprising the bare ITO anode is approximately 5 lm/W at a luminance of 1000
31 cd/m². The increased power efficiency suggests that the chlorine functionalization of the ITO
32 anode has a significant effect on power efficiency.

1 **[00123]** Given the improved alignment of the work function of the chlorinated ITO anode and
2 the HOMO of the CBP layer, it may be possible to forego the several HILs and HTLs that are
3 typically required in such a device construction without an unacceptable loss of efficiency.
4 Foregoing the requirement for HTLs is advantageous, as the number of processing steps
5 required to construct the OLED device may be reduced, thereby increasing the manufacturing
6 yield of OLED devices and reducing costs associated with their production.

7 **[00124]** The halogen functionalized electrode in the examples above contributes little series
8 impedance to the device. For example, a chlorine-functionalized ITO anode was prepared for
9 use in a single-carrier hole-only organic device. The structure of the device is as follows:
10 anode/ α -NPD (536 nm)/Ag (50 nm). A first device comprising a bare UV ozone treated anode
11 was compared to a second device having a UV ozone treated ITO anode coated with 1 nm of
12 vacuum deposited MoO₃, and a third device comprising a chlorine-functionalized ITO anode.
13 The hole injection barrier height between the anode and the α -NPD organic layer was measured
14 for each device using UPS. The hole injection barrier height was 0.6 eV for bare UV ozone
15 treated ITO, 0.45 eV for UV ozone treated ITO coated with 1 nm of vacuum deposited MoO₃
16 and 0.45 eV for chlorine-functionalized ITO. The performance of the device with the UV ozone
17 treated ITO coated with 1 nm MoO₃ may initially be expected to be the same as the device with
18 the chlorine-functionalized ITO since the barrier height for holes is the same for both devices.

19 **[00125]** FIG. 26 is a diagram showing the current-voltage characteristics of the example
20 single-carrier hole-only organic devices described above. The current density at a given voltage
21 is highest for the device with the chlorine-functionalized ITO anode. The device with the UV
22 ozone treated ITO anode coated with 1 nm MoO₃ is nevertheless exhibiting a higher current
23 density at any given voltage than the device with the bare UV ozone treated ITO anode due its
24 lower hole injection barrier height. Unexpectedly, the current density for the device with the
25 chlorine-functionalized ITO anode is higher at a given voltage than for the device with the UV
26 ozone treated ITO anode coated with 1 nm MoO₃, despite the same barrier height for holes. The
27 lower current density in the device with the UV ozone treated ITO anode coated with 1 nm MoO₃
28 shows that the MoO₃ layer introduces a series impedance into the device.

29 **[00126]** As was described above, a substrate may also be functionalized using a plasma.
30 FIG. 27 is a plasma system for functionalizing a substrate. The system comprises a reaction
31 chamber 2608, which is grounded 2612. The system may comprise a plurality of rods 2620
32 which support a substrate support 2626 upon which the substrate 2652 may be placed. The
33 substrate 2626 may be placed in electrical communication with the substrate support 2626. The

1 substrate 2652 may be deposited on a non-conductive mechanical support 2650, for example,
2 glass. A high energy plasma shield 2624 is also provided. The plasma shield 2624 may also
3 be supported by the rods 2620. The plasma shield 2624 is also grounded.

4 **[00127]** A radio frequency (RF) power source 2610 provides power to the powered electrode
5 2611. The reaction chamber 2608 comprises an inlet 2614 through which a gas comprising a
6 precursor may be pumped and an outlet 2616 through which the vacuum chamber can be
7 evacuated by a vacuum pump. The precursor may be a liquid or a gas. When the powered
8 electrode 1611 is powered by the RF power source 2610, a plasma may be generated between
9 the powered electrode 1611 and the grounded portions of the system including the reaction
10 chamber 2608. In particular, the highest energy plasma is generated in the region of the
11 highest electric field, which may be between the powered electrode 2611 and the plasma shield
12 2624. However, plasma may also be generated elsewhere in the chamber 2608.

13 **[00128]** The plasma causes the dissociation of any precursors in the reaction chamber. The
14 dissociated precursors may then react with the surface of the substrate 2652 to begin to form a
15 monolayer 2654. As is well known, particles in the plasma may have a substantial kinetic
16 energy. The plasma shield 2624 prevents the plasma having the highest kinetic energy from
17 directly impinging on the surface of the substrate 2652, thereby reducing the etching effects of
18 the substrate 2652.

19 **[00129]** By way of example, the chamber may be pumped down to about 250 mTorr and 1,2-
20 dichlorobenzene may be leaked in as a precursor for an ITO substrate. The substrate may be
21 treated for approximately 5 minutes. Etching of the substrate was minimized due to the
22 positioning of the substrate behind the plasma shield 2624. The functionalized substrate may
23 be cleaned to remove residual contaminates.

24 **[00130]** It can be appreciated that potential applications of organic optoelectronic devices
25 comprising substrates functionalized according to the method described herein comprise
26 organic photovoltaics, OLEDs, organic thin film transistors, and biomedical devices. It will be
27 appreciated that although reference is made to organic electronic devices comprising TCO
28 functionalized electrodes, inorganic electronic devices may comprise functionalized TCO
29 electrodes. For example, LCD electrodes may be functionalized using the process as described
30 herein.

1 **[00131]** Other potential applications of substrates functionalized according to the methods
2 described above comprise functionalizing a substrate to adjust surface energy, and templating
3 growth of materials on a substrate that has been selectively functionalized.

4 **[00132]** It will be appreciated that although examples were provided disclosing the
5 functionalization of TCO substrates, other types of substrates may be functionalized. For
6 example, metals, polymers (including conductive polymers), and ceramics may be
7 functionalized with a species using the process as described herein.

8 **[00133]** Although example methods of functionalizing substrates are provided above, it will
9 be appreciated that substrates may be functionalized using methods other than those
10 described. For example, it will be appreciated that electrodes comprising TCO substrates may
11 be functionalized with up to about a monolayer of a halogen species using methods other than
12 those described above.

13 **[00134]** Although the above has been described with reference to certain specific example
14 embodiments, various modifications thereof will be apparent to those skilled in the art without
15 departing from the scope of the claims appended hereto.

16
17

We Claim

1. A method of increasing a work function of a surface of an electrode, the method comprising:
obtaining an electronegative species from a precursor using electromagnetic radiation; and
reacting the surface of the electrode with the electronegative species to bond the electronegative species to the surface.
2. The method of claim 1 wherein the electronegative species is a halogen.
3. The method of any one of claims 1-2 wherein the electromagnetic radiation has a wavelength of at least 100 nm.
4. The method of any one of claims 1-3 wherein the electromagnetic radiation has a wavelength of less than 400 nm.
5. The method of any one of claims 1-4 further comprising cleaning the surface of the electrode prior to reacting the surface of the electrode with the electronegative species.
6. The method of any one of claims 1-5 wherein the electrode is a transparent conducting oxide.
7. The method of claim 6 wherein the transparent conducting oxide is ITO.
8. The method of any one of claims 1-7 wherein the electronegative species is selected to obtain an electrode of a predetermined work function.
9. The method of any one of claims 1-8 wherein surface coverage of the species is selected to obtain an electrode of a predetermined work function.
10. The method of any one of claims 2-9 wherein up to a monolayer of halogen is functionalized to the substrate.
11. The method of any one of claims 2-10 wherein the halogen is chlorine.
12. The method of any one of claims 1-11 wherein the precursor is a volatile liquid.
13. The method of any one of claims 1-11 wherein the precursor is a gas.
14. The method of any one of claims 1-13 wherein the substrate is functionalized to increase its stability in air.
15. An electrode made by the method of claim 1 comprising a surface functionalized with an electronegative species.
16. An organic electronic device comprising the electrode of claim 15.

17. An electrode having a surface functionalized with at least 20% of a monolayer of halogen wherein the electrode comprises a transparent conductor.
18. The electrode of claim 17, wherein the surface of the electrode is functionalized with up to a monolayer of halogen.
19. The electrode of claim 18, wherein the transparent conductor is indium tin oxide, tin oxide, indium oxide, cadmium oxide, fluorine tin oxide, cadmium tin oxide, zinc tin oxide, antimony tin oxide, aluminum zinc oxide, titanium zinc oxide, gallium zinc oxide, aluminum gallium zinc oxide, indium gallium zinc oxide, gallium indium oxide, zinc indium oxide, gallium indium tin oxide, zinc indium tin oxide, titanium indium oxide, tin cadmium oxide, indium cadmium oxide, zinc cadmium oxide, aluminum cadmium oxide, gold, or zinc oxide.
20. The electrode of any one of claims 18 to 19, wherein the halogen is chlorine, fluorine, bromine, or iodine.
21. The electrode of claim 17, wherein the electrode comprises indium tin oxide, and the surface of the electrode is functionalized with at least 20% of a monolayer of chlorine.
22. The electrode of claim 21, wherein the surface of the electrode is functionalized with up to a monolayer of chlorine.
23. The electrode of claim 17, wherein the electrode comprises fluorine tin oxide, and the surface of the electrode is functionalized with at least 20% of a monolayer of fluorine.
24. The electrode of claim 23, wherein the surface of the electrode is functionalized with up to a monolayer of fluorine.
25. The electrode of claim 17 wherein the electrode comprises indium tin oxide and the halogen is chlorine.
26. The electrode of claim 17 wherein the electrode comprises fluorine tin oxide and the halogen is fluorine.
27. An organic electronic device comprising the electrode of any one of claims 17-26.
28. The organic electronic device of claim 16 comprising an organic light emitting diode.
29. The method of claim 10 wherein the surface is functionalized with at least 20% of a monolayer of halogen.
30. The method of claim 1 wherein the electromagnetic radiation has a wavelength corresponding to the ultraviolet region of the electromagnetic spectrum.
31. The electrode of claim 15 wherein the surface is functionalized with at least 20% of a monolayer of halogen.

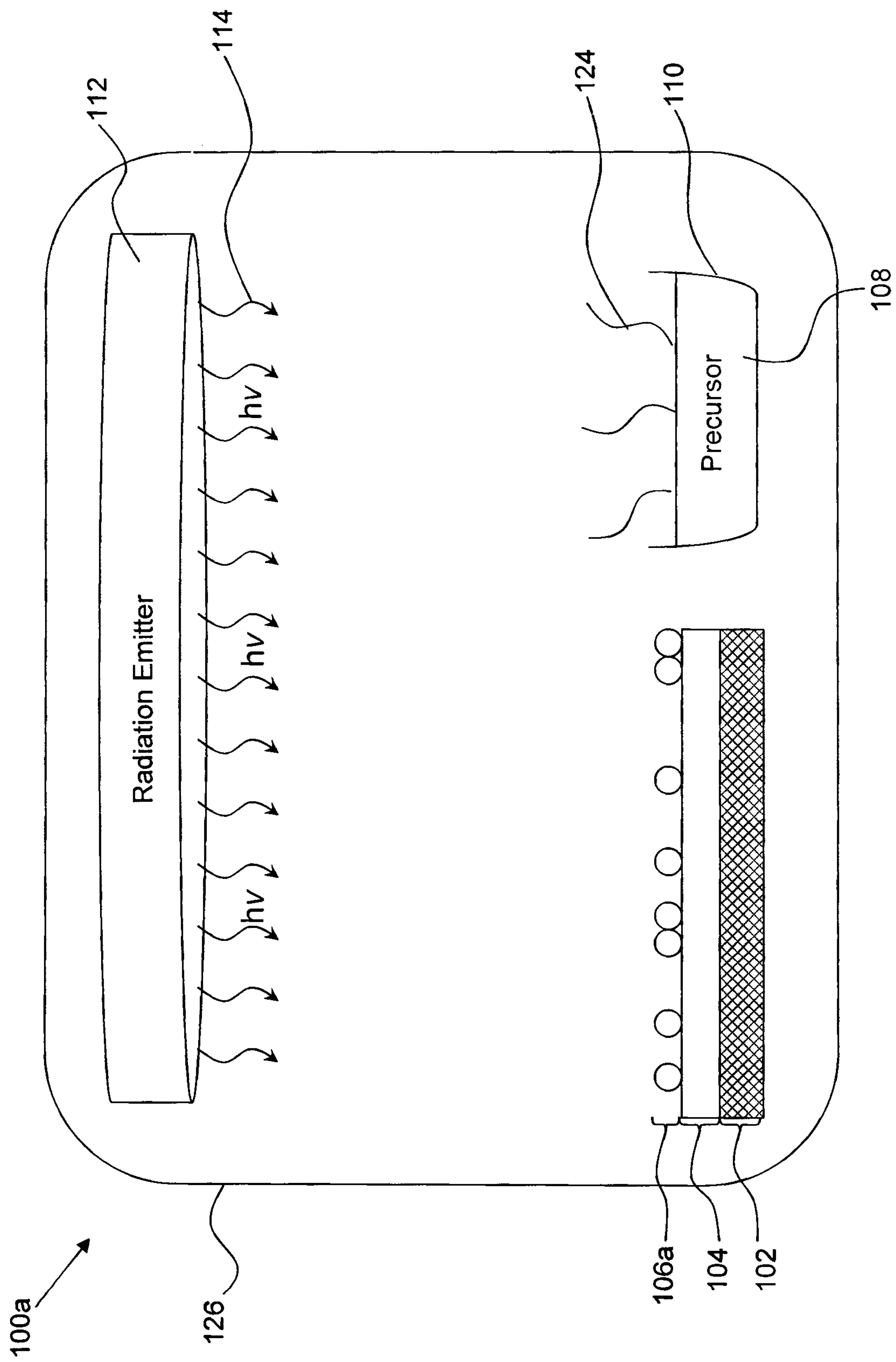


FIG. 1

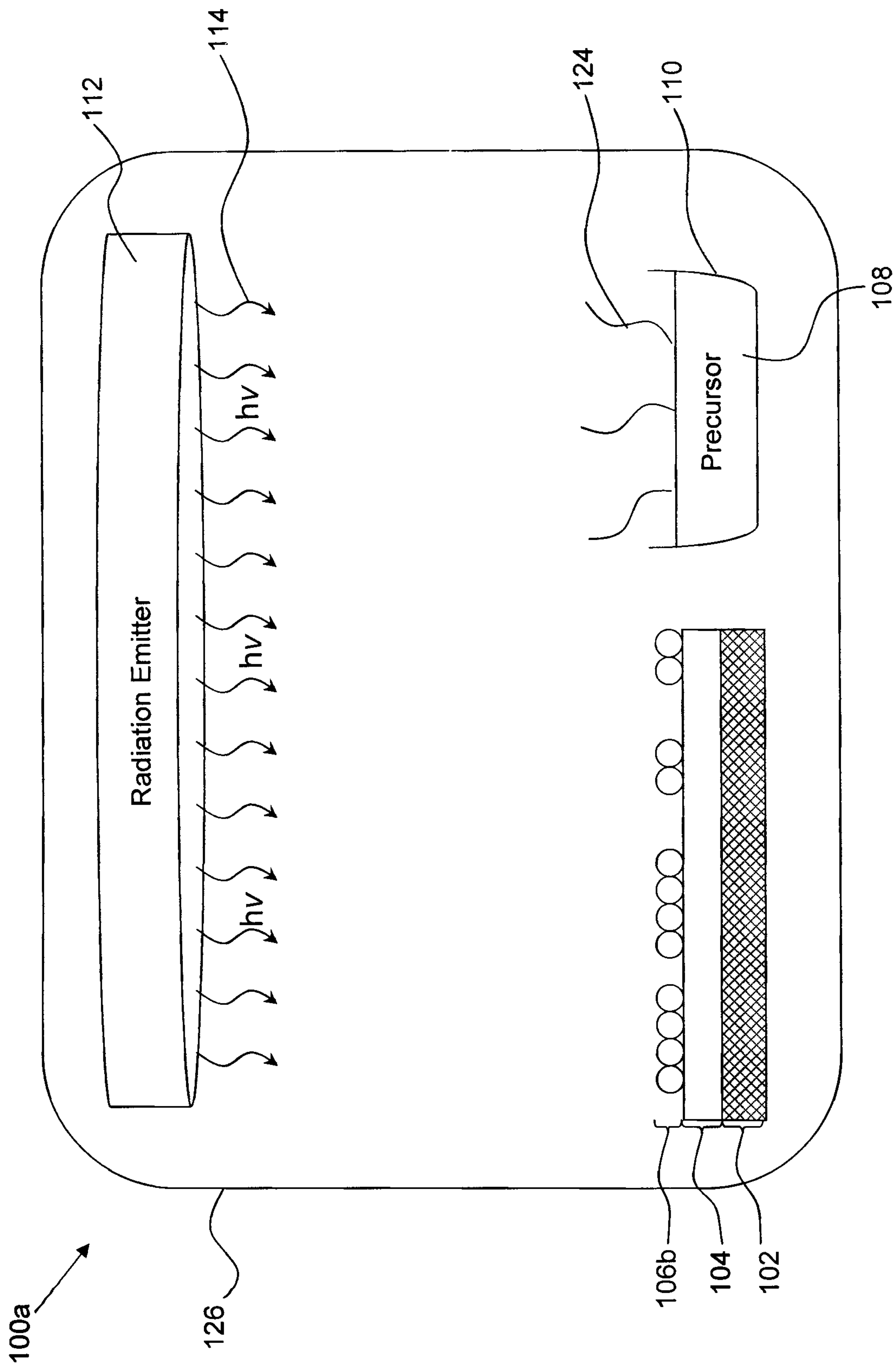


FIG. 2

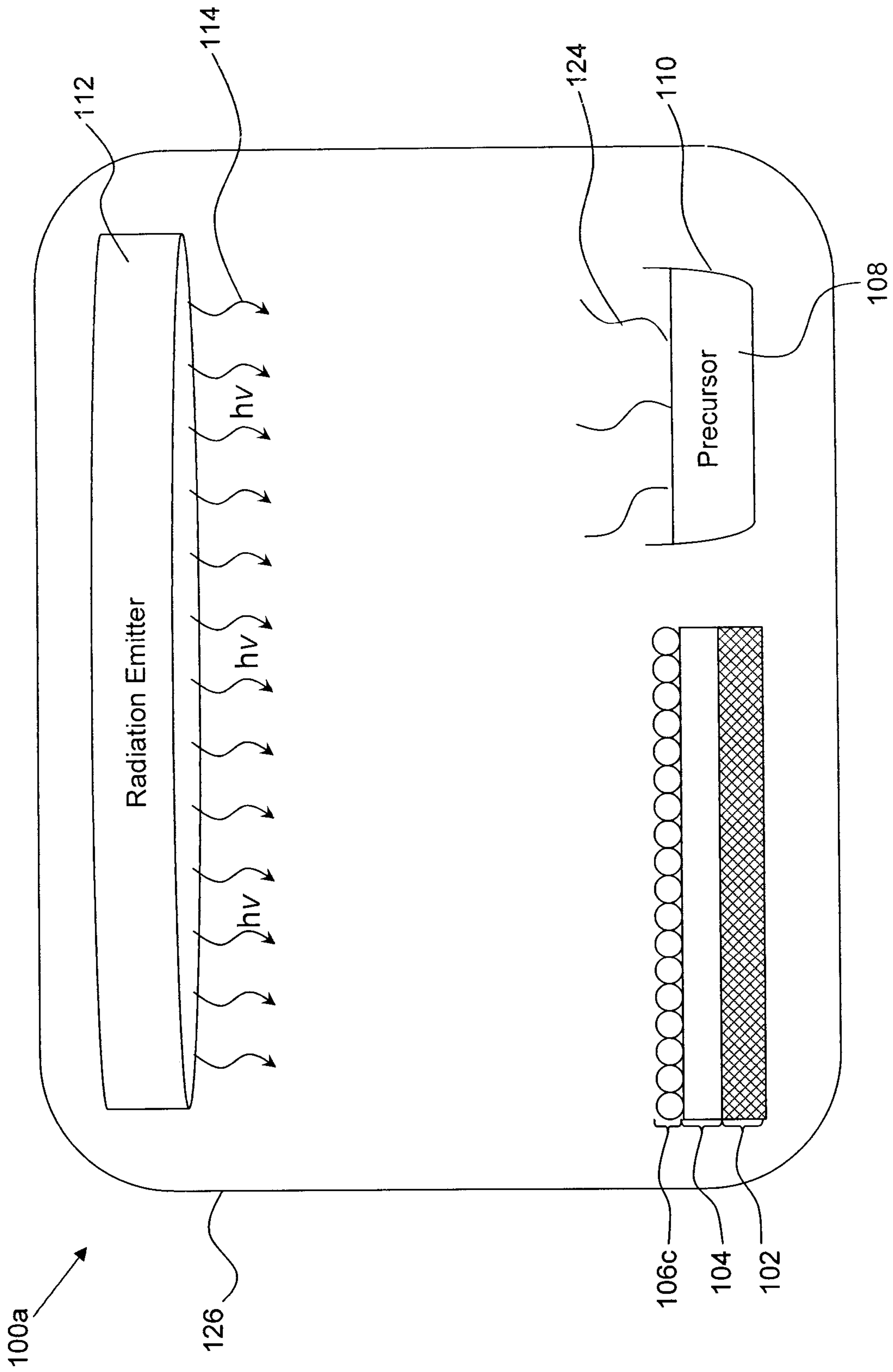


FIG. 3

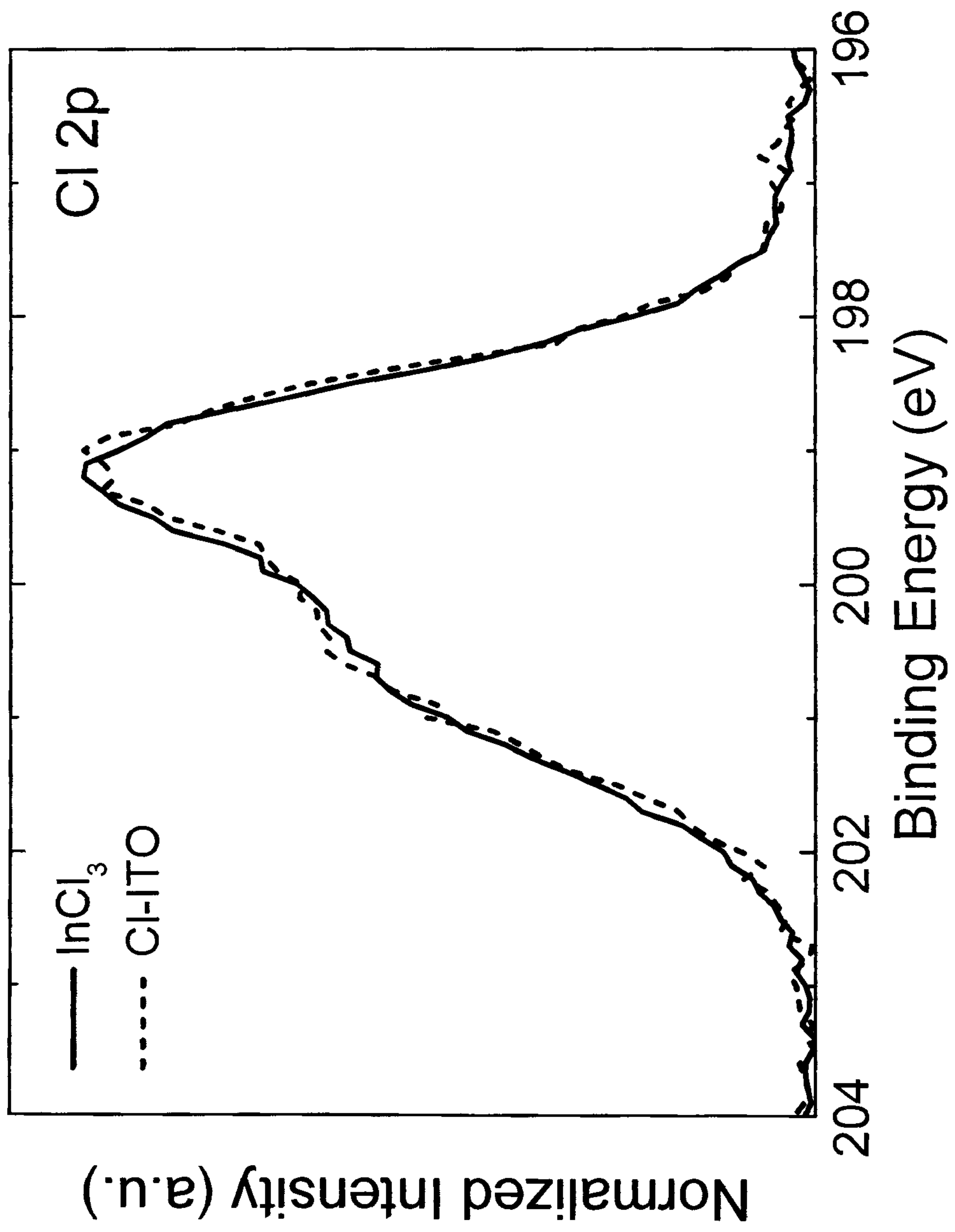


FIG. 4

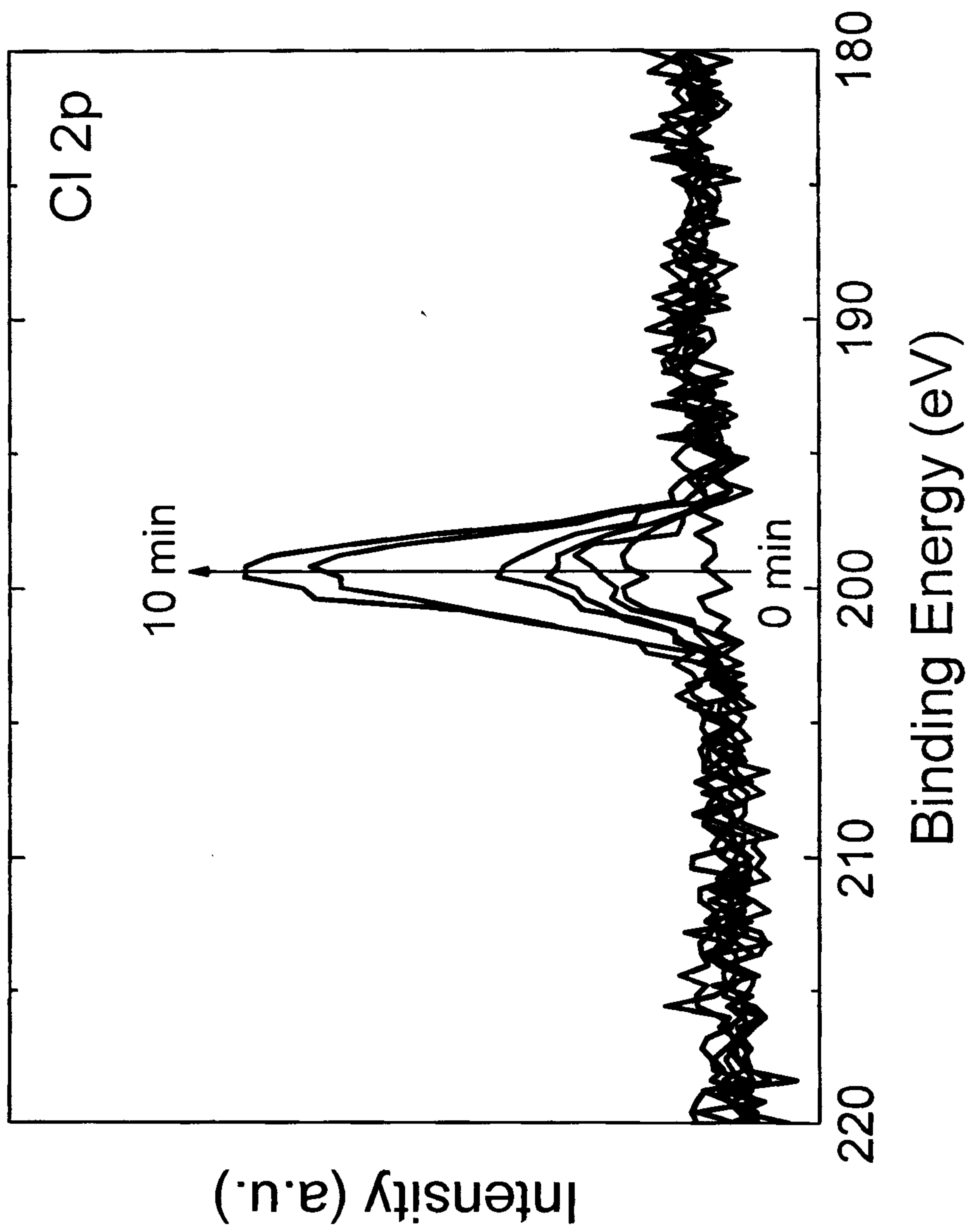


FIG. 5

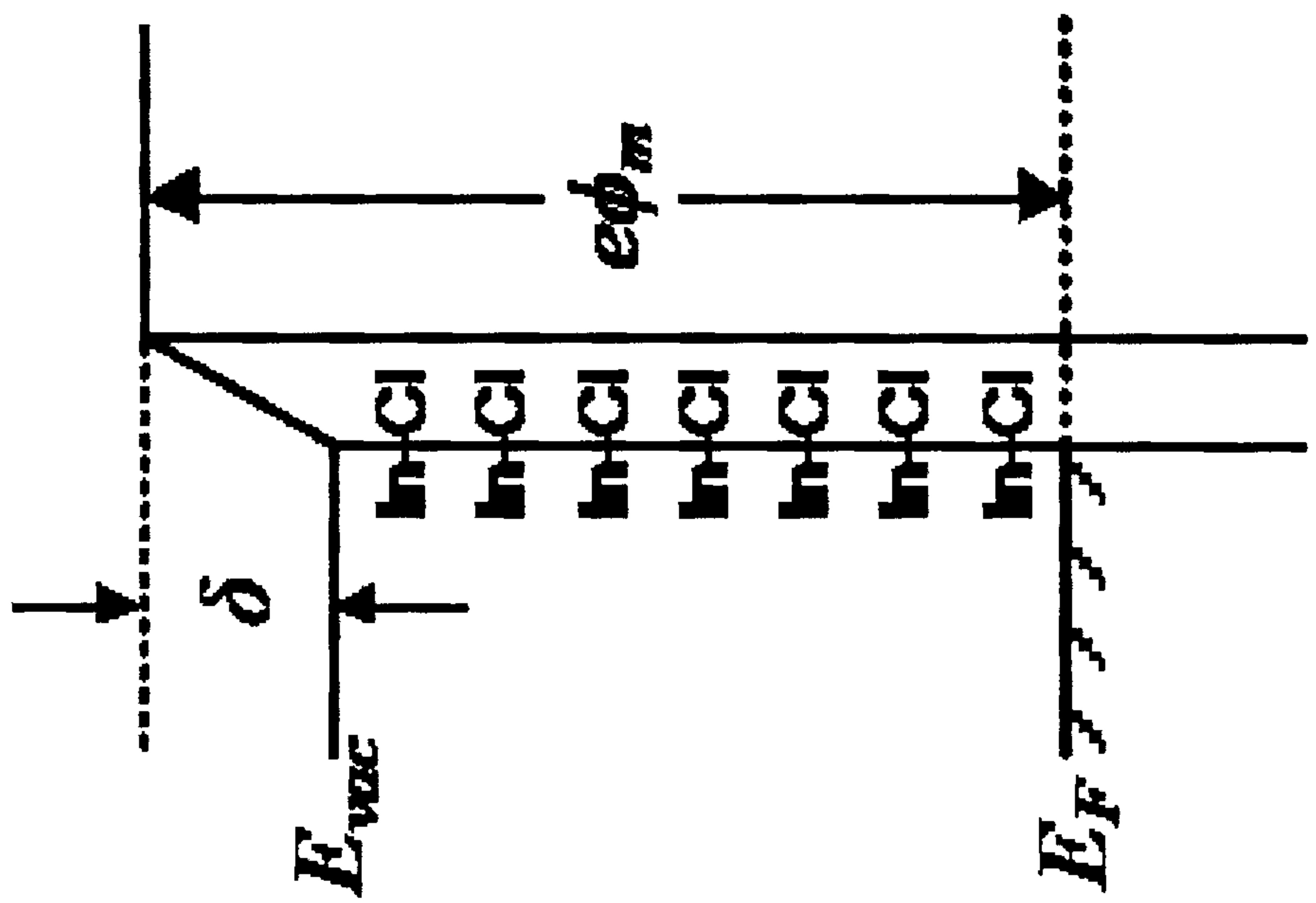


FIG. 7

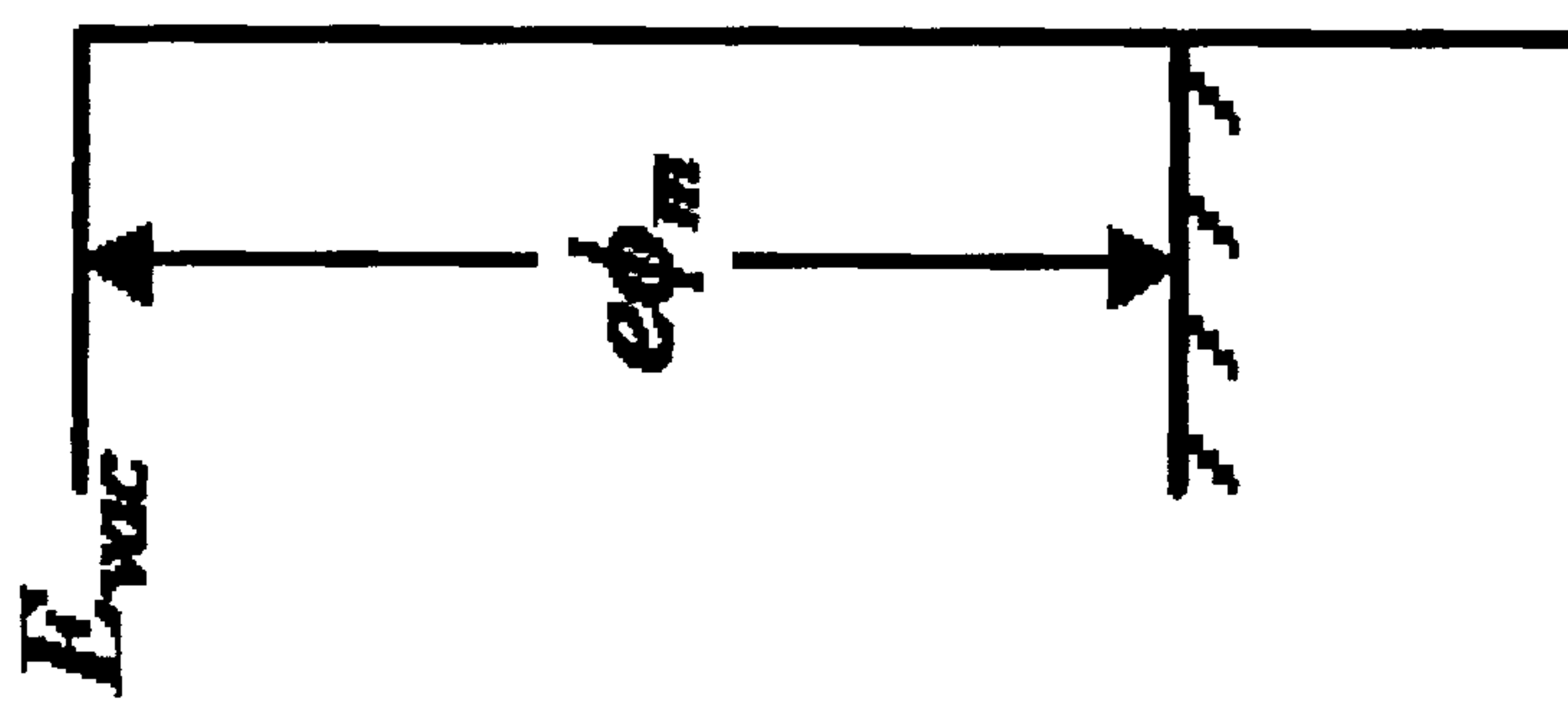


FIG. 6

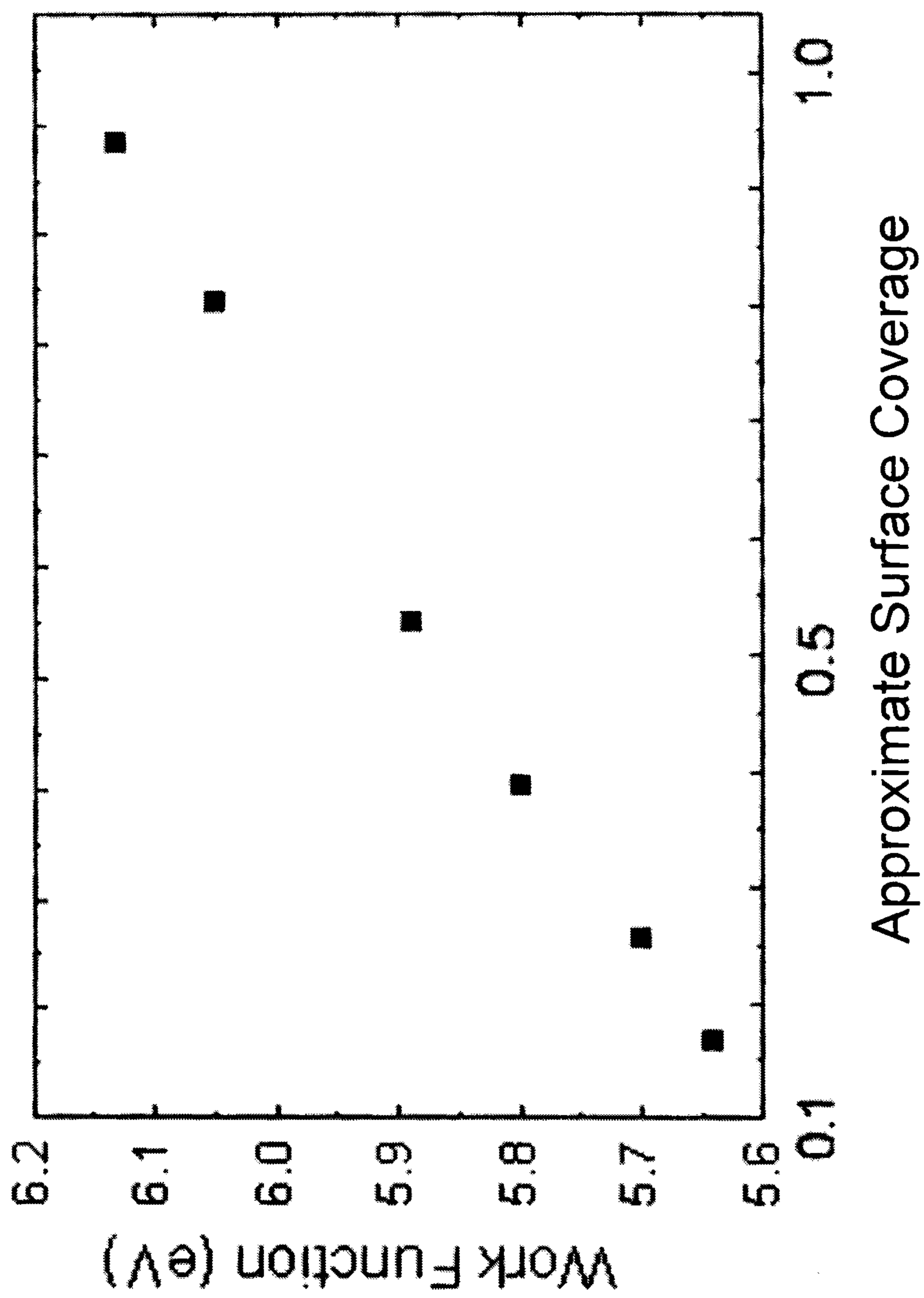


FIG. 8

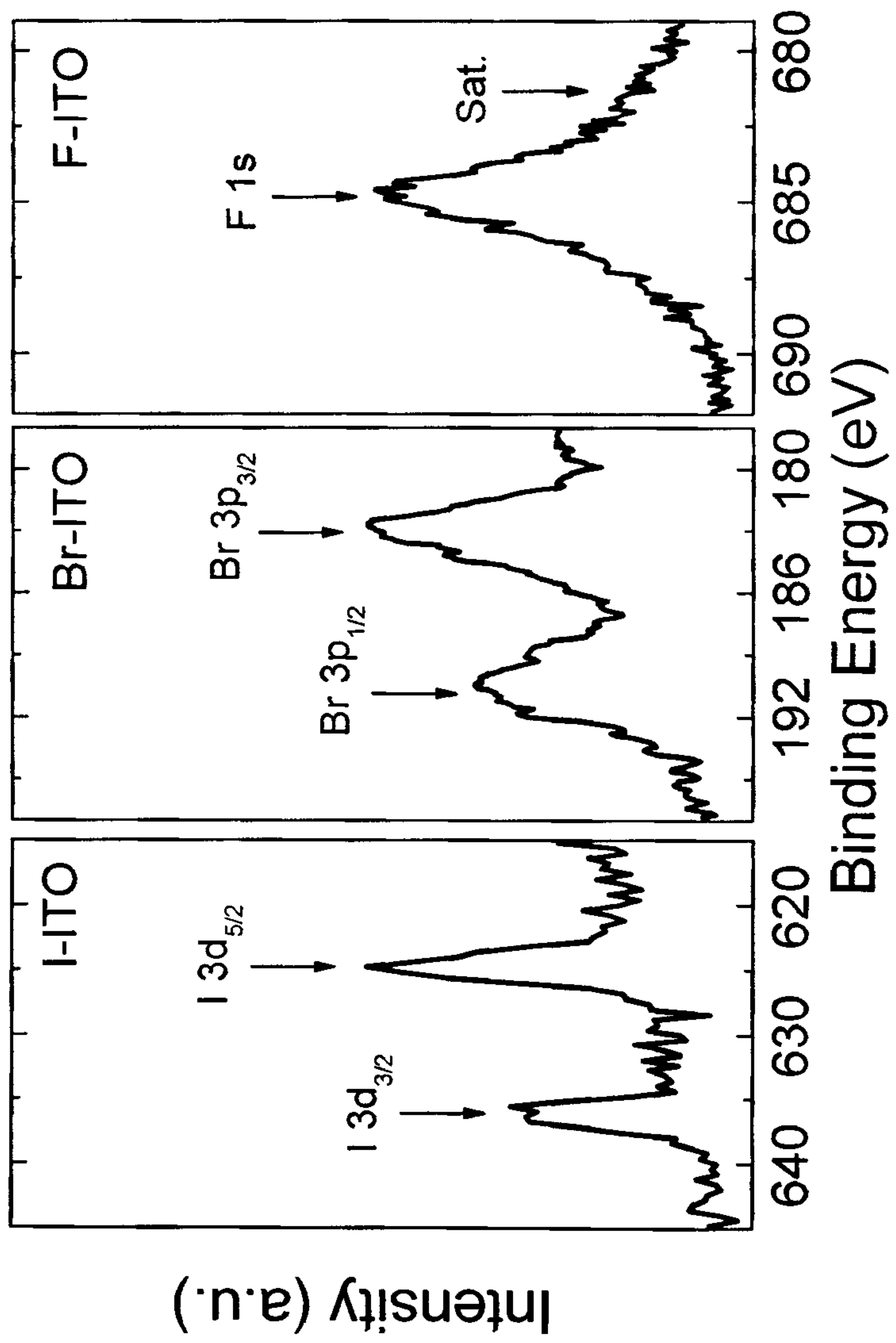


FIG. 9

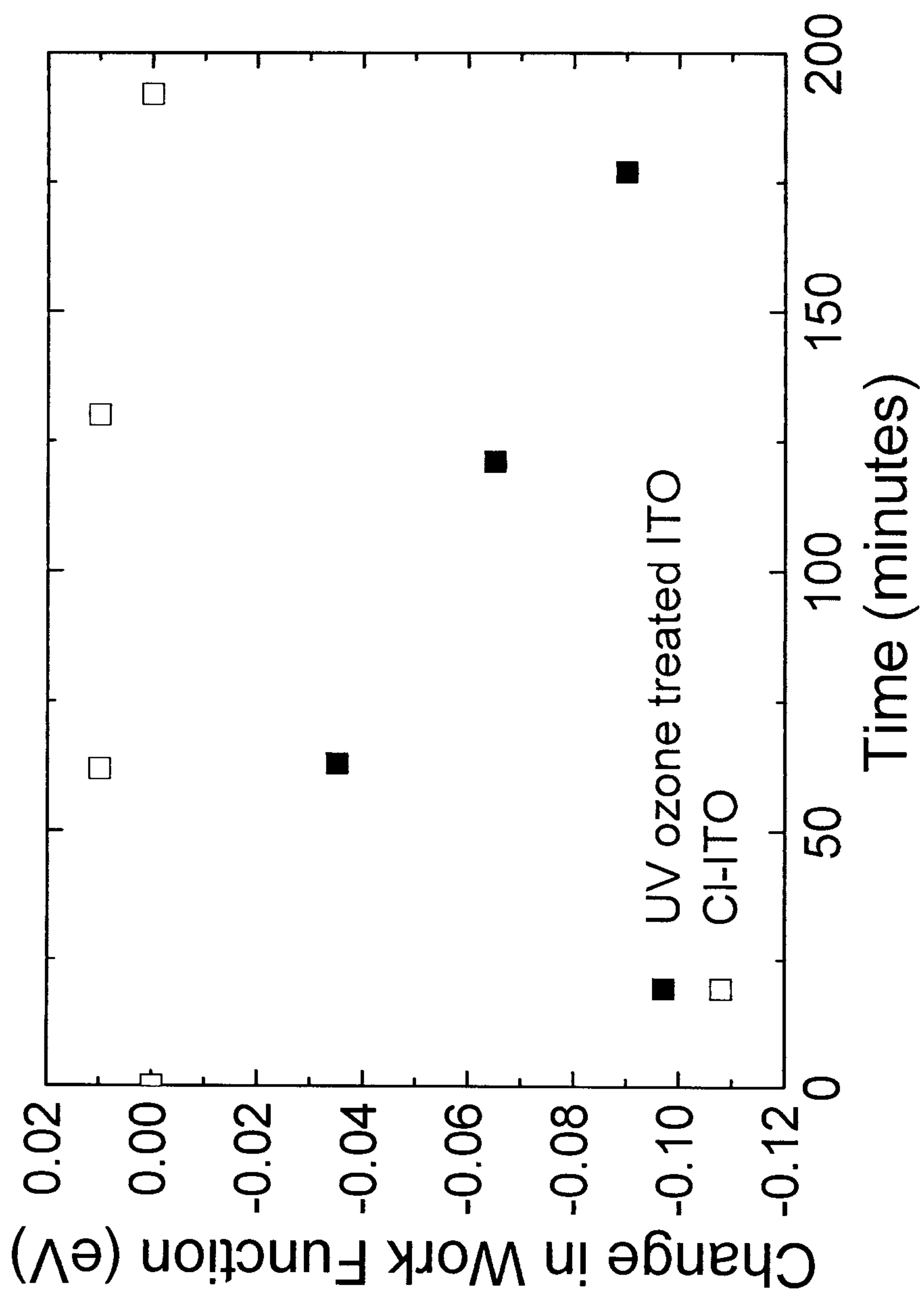


FIG. 10

Material	Work Function (eV) after exposure to air	
	TCO	Chlorinated TCO
NiO	5.3	5.9
MoO3	5.3	6.0
WO3	5.2	5.9
AuOx	5.6	6.2

FIG. 11

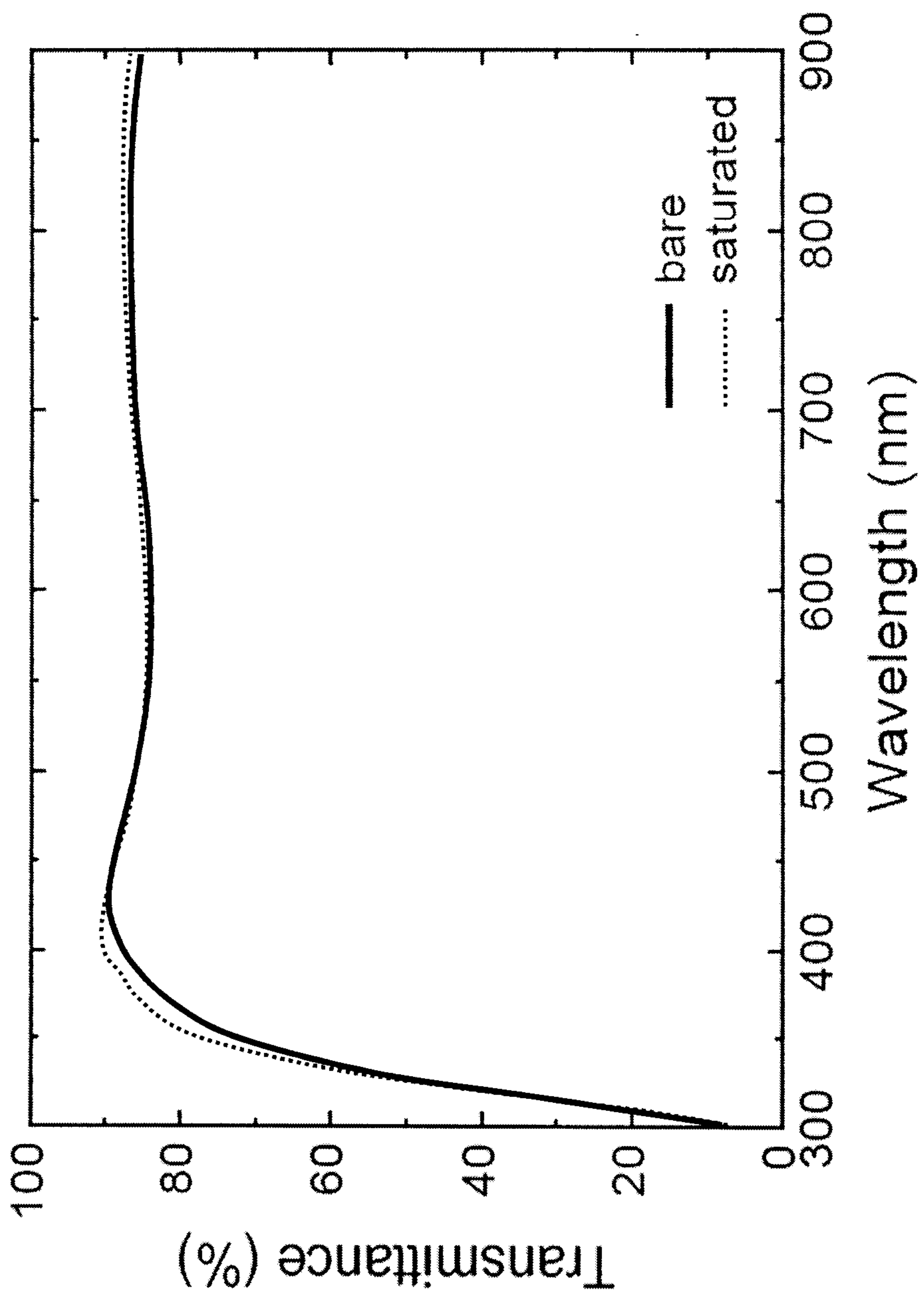


FIG. 12

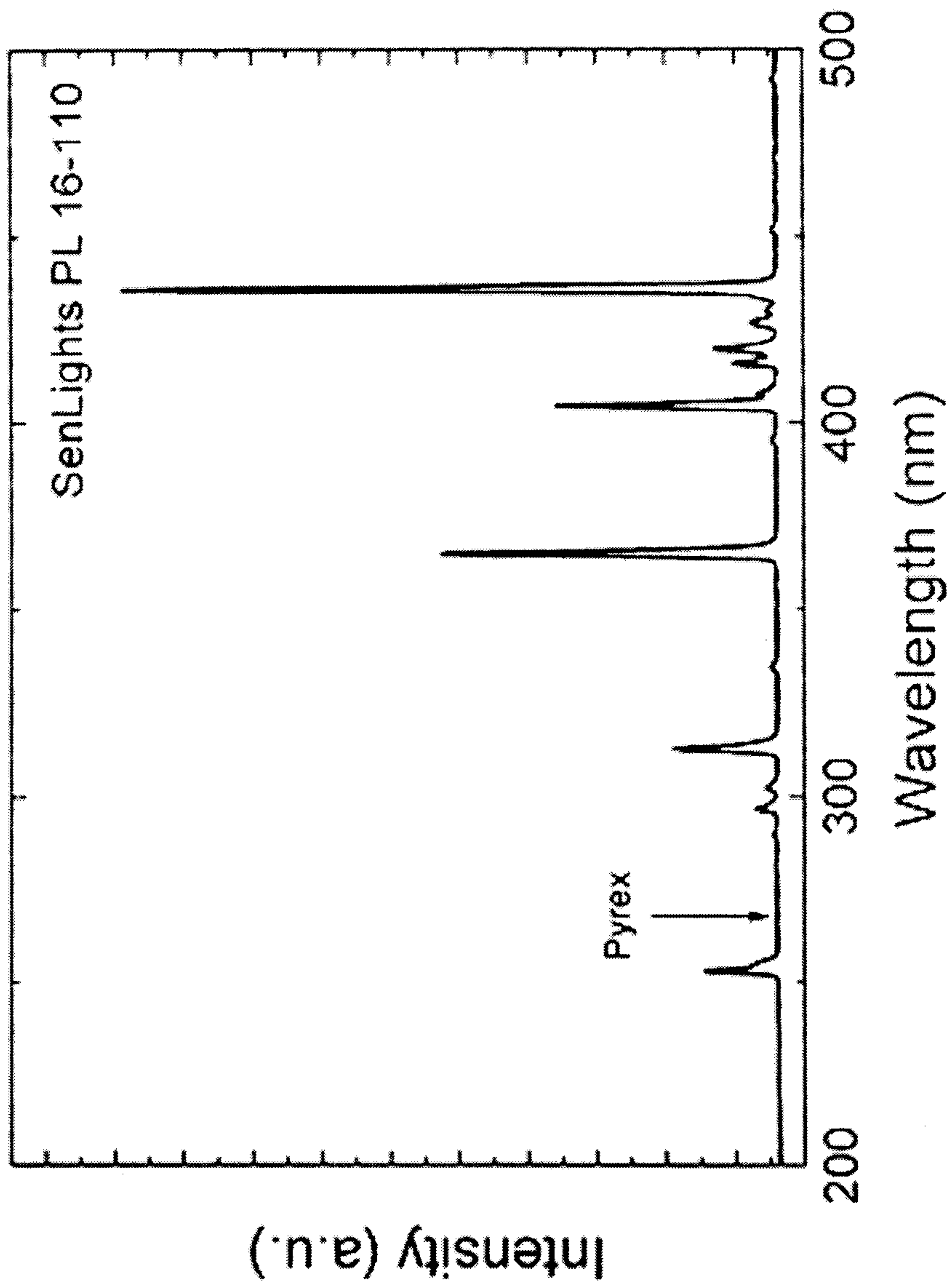


FIG. 13

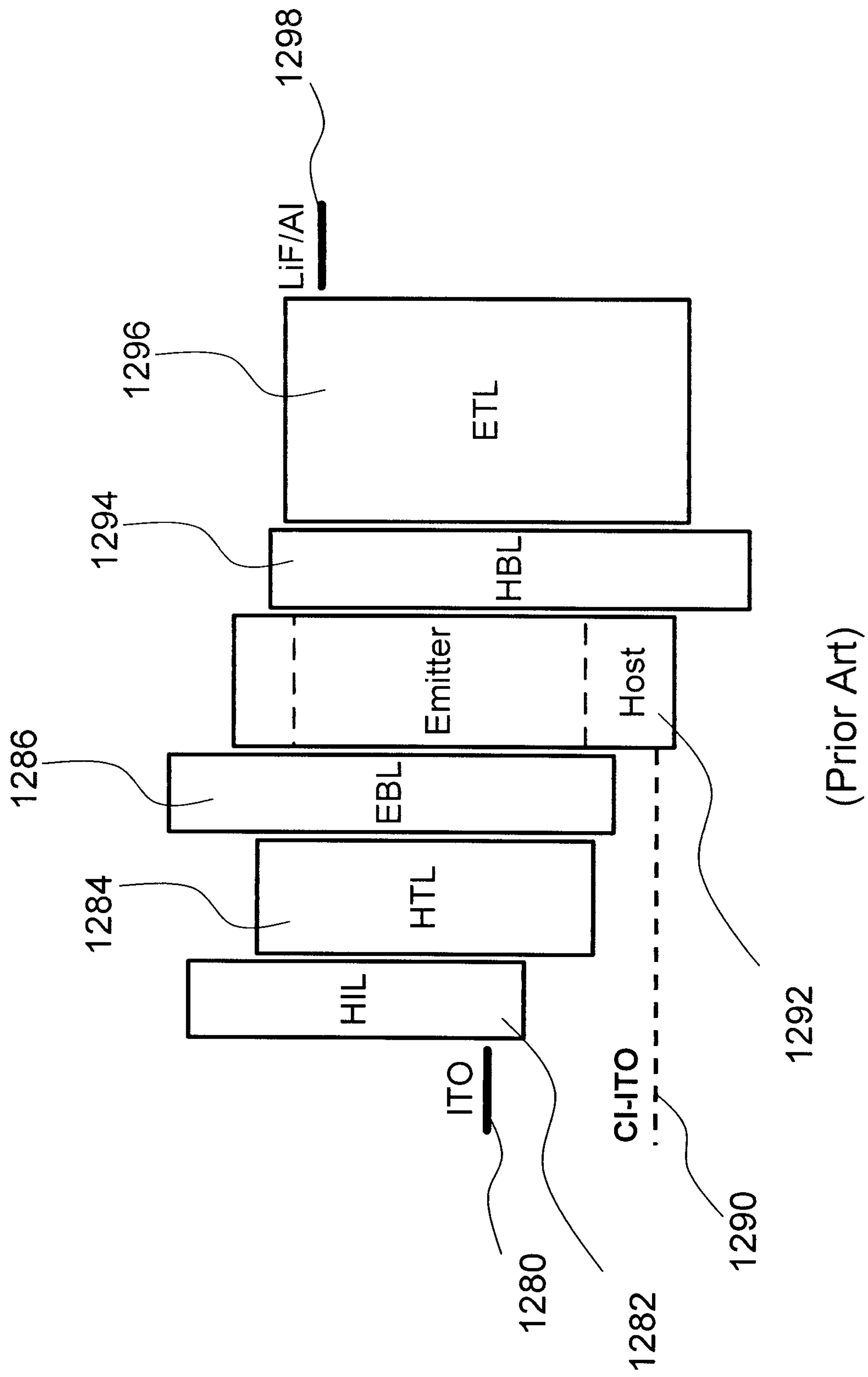


FIG. 14

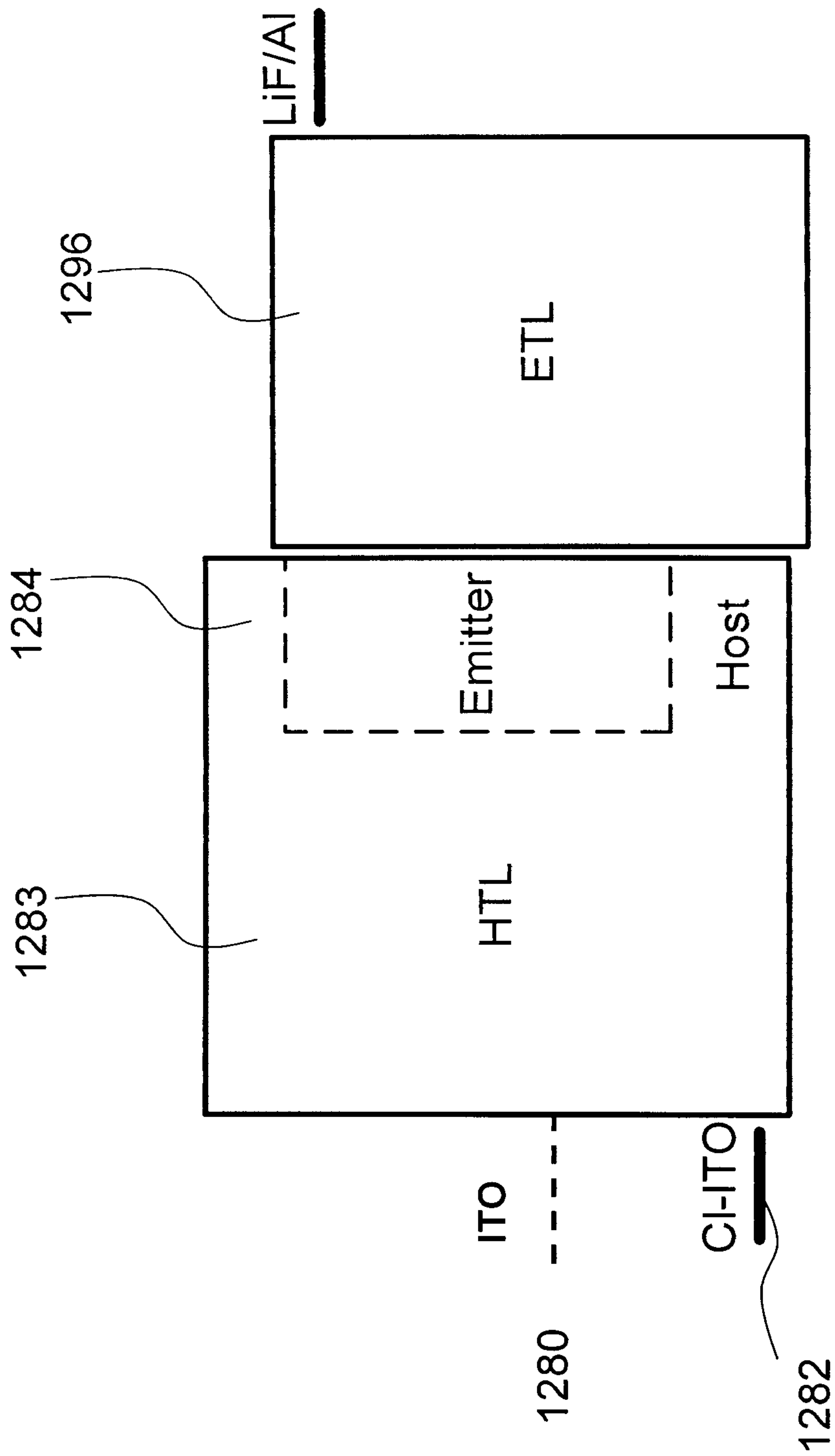


FIG. 15

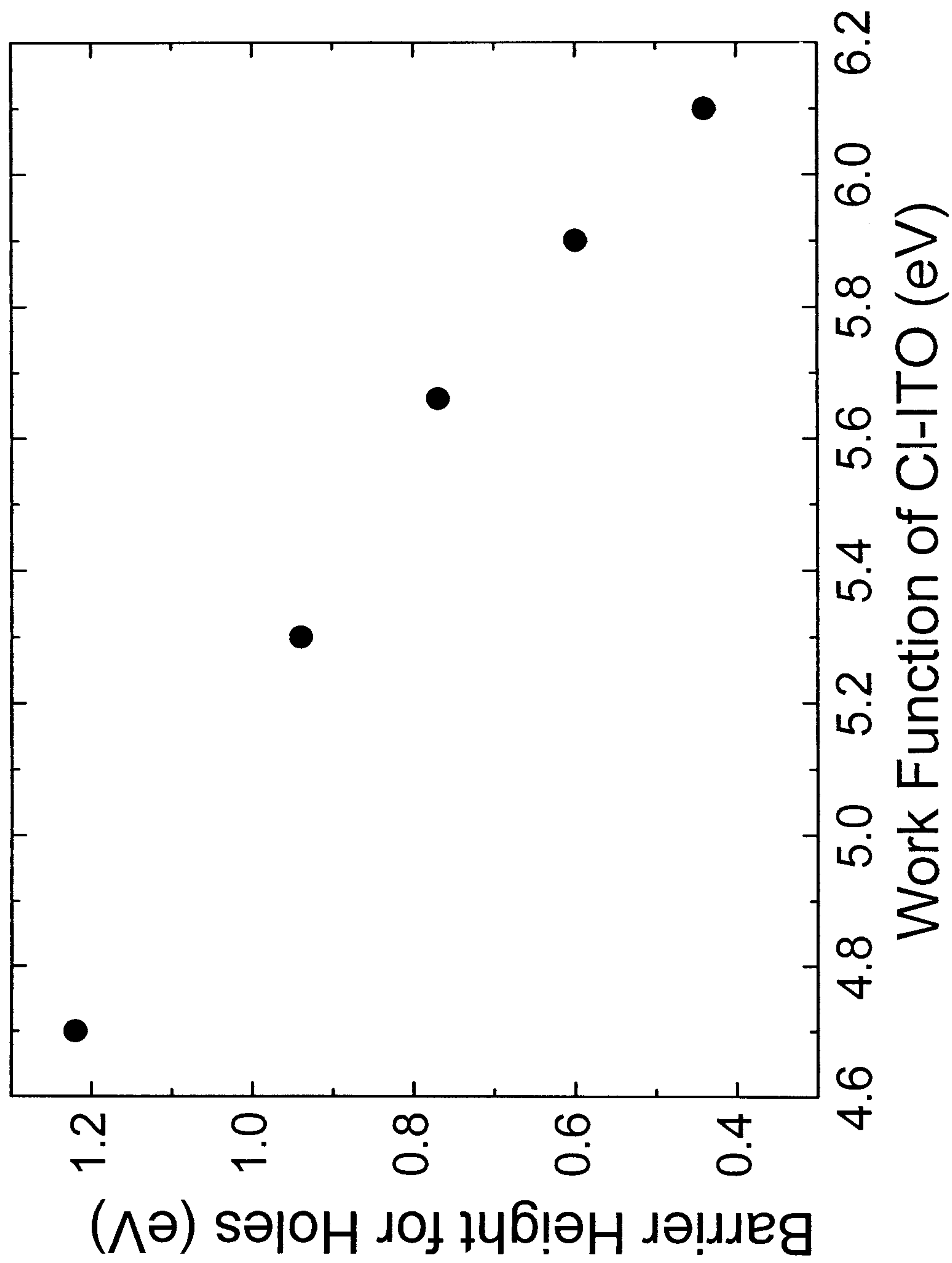


FIG. 16

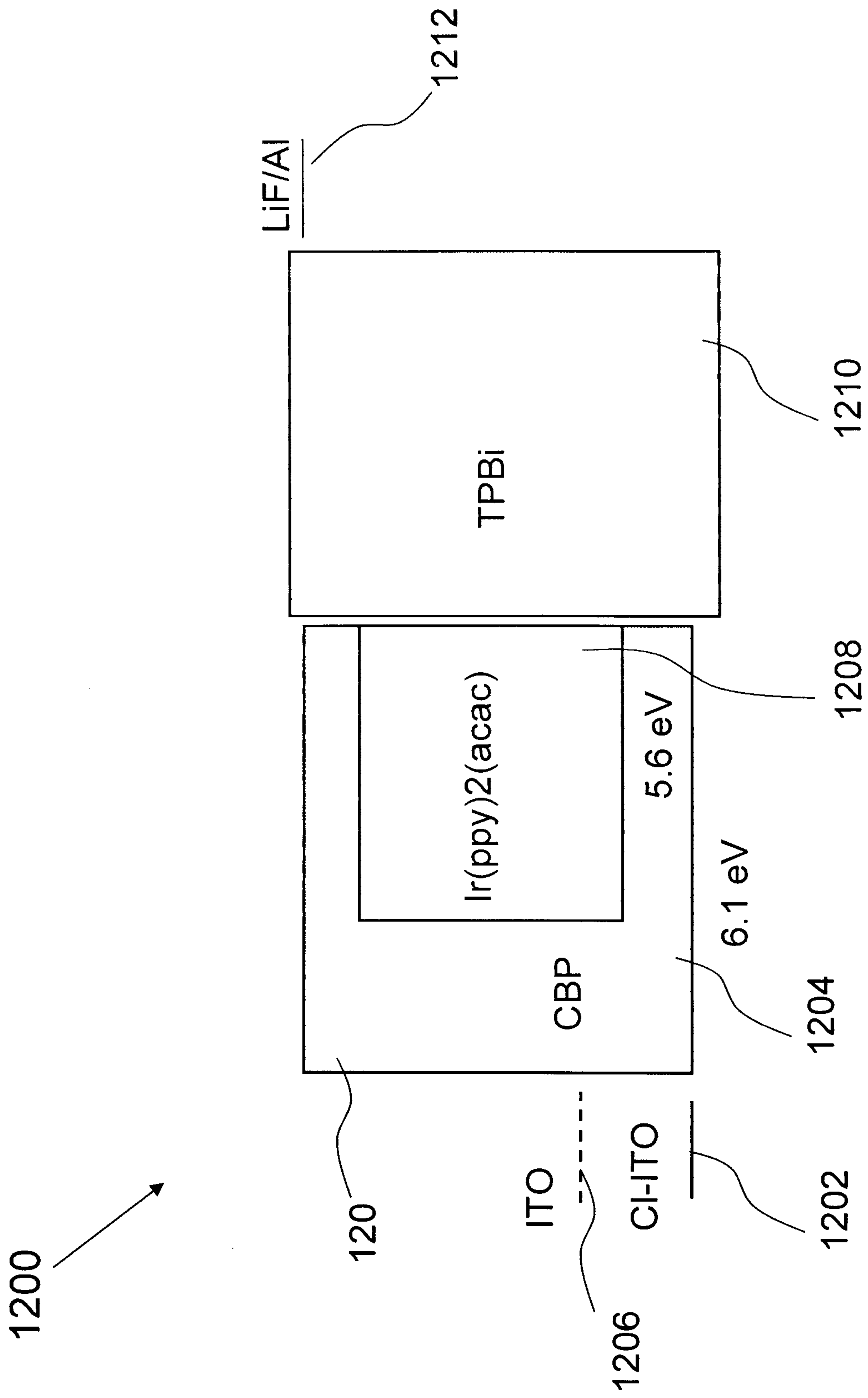


FIG. 17

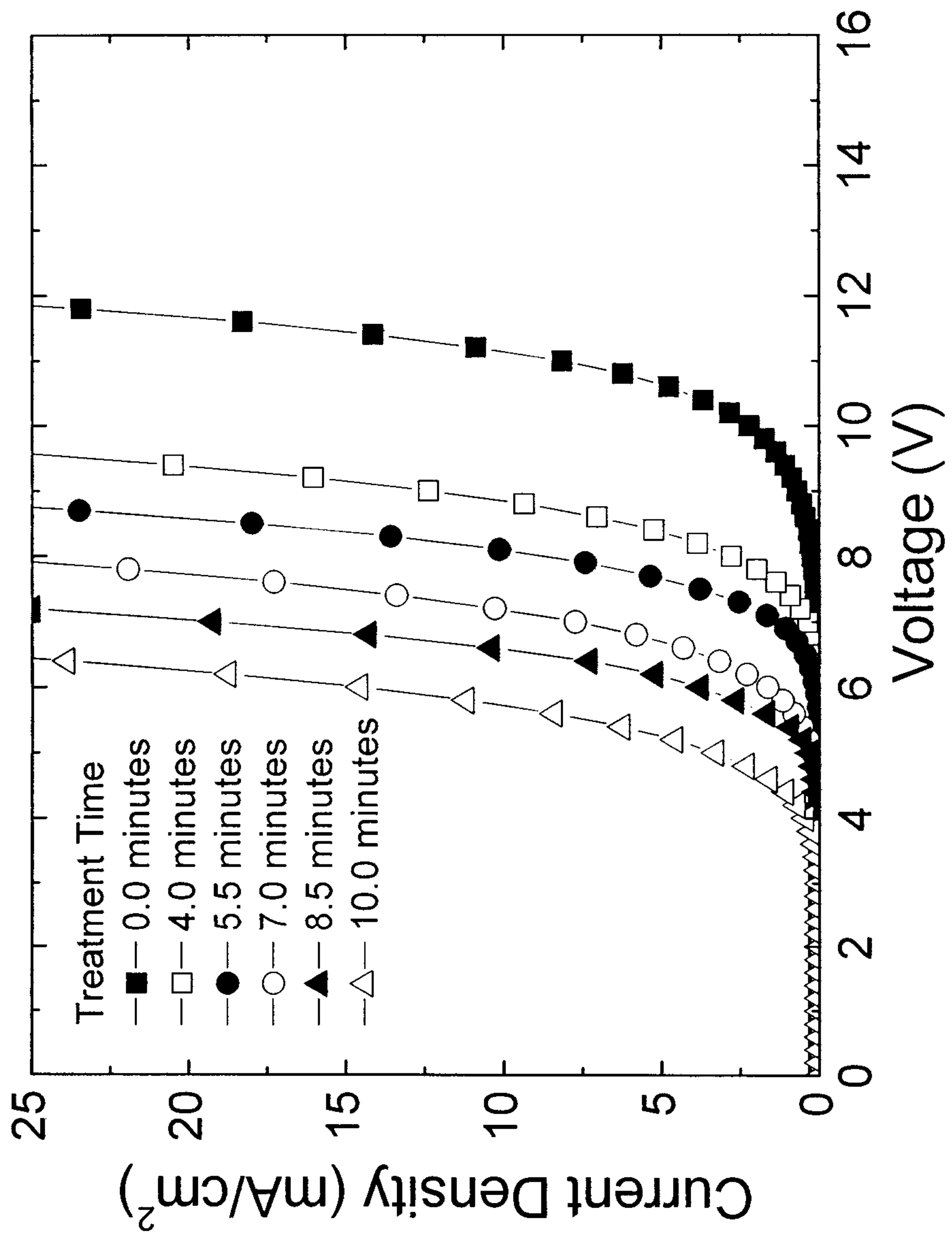


FIG. 18

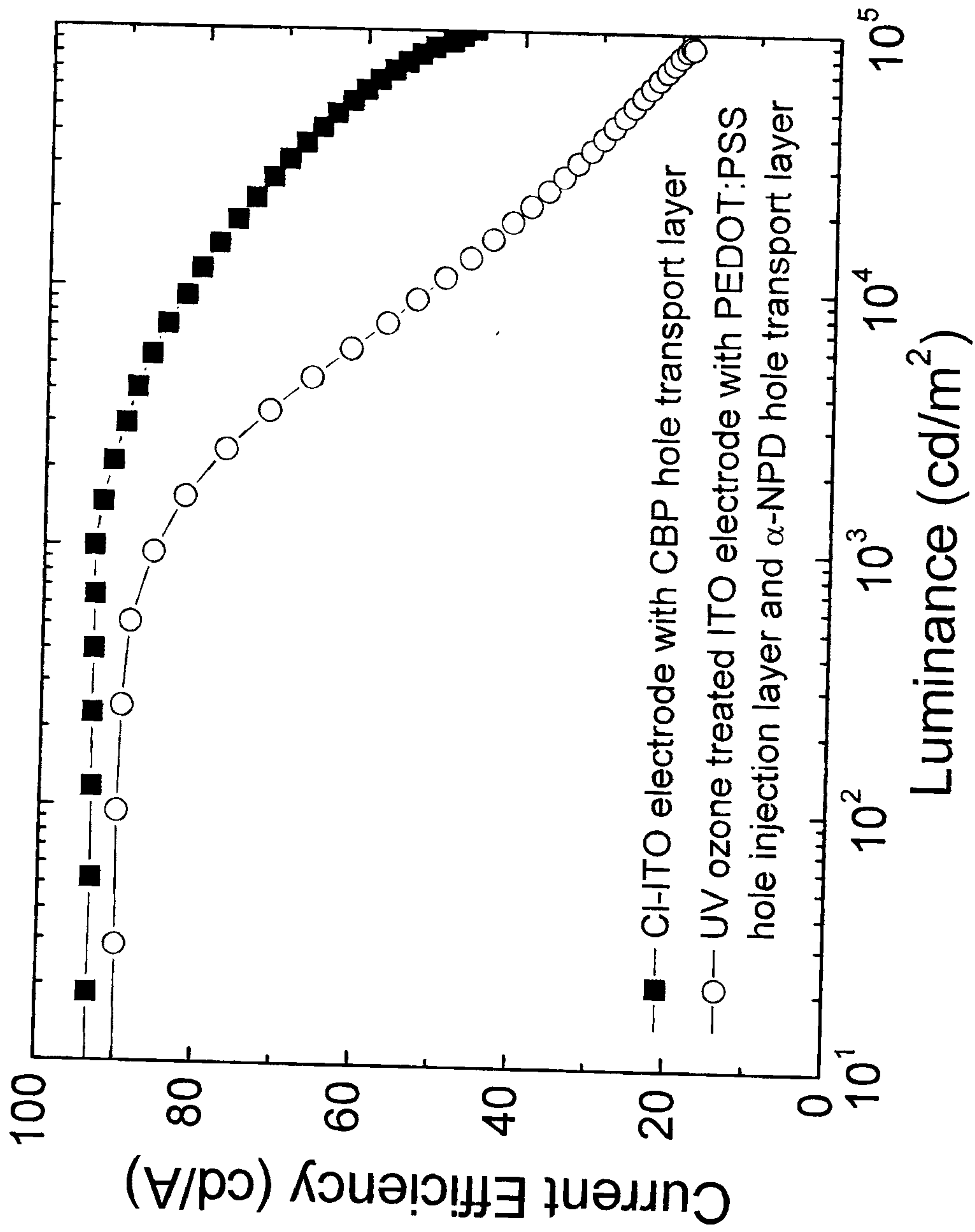


FIG. 19

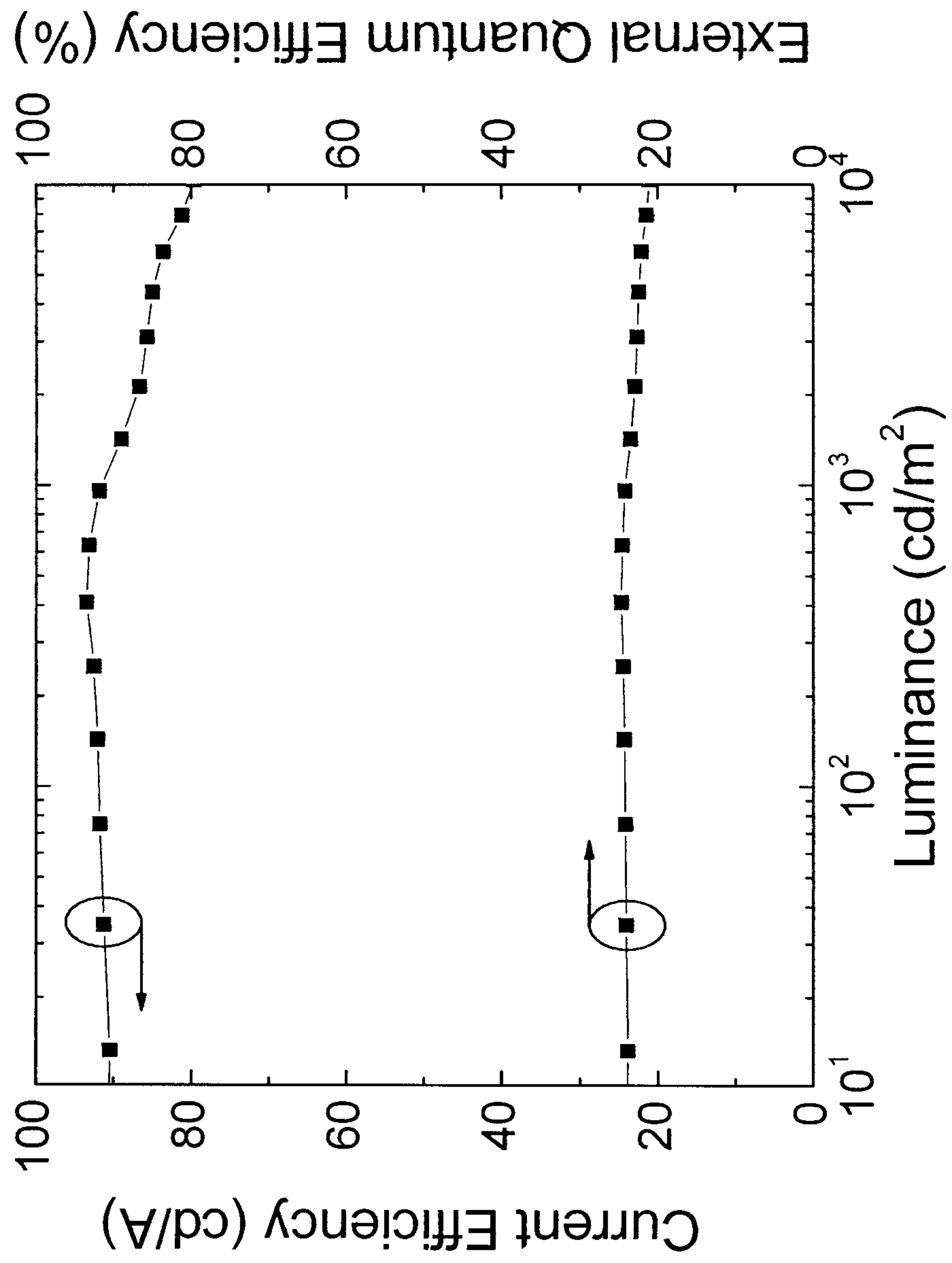


FIG. 20

Reference	# of Organic Layers	# of Organic Molecules	EQE (%) at 10,000 cd/m ²
<i>Appl. Phys. Lett.</i> 85 , 3911 (2004).	6	7	~16
CF4 Plasma-treated Anode <i>Jap. J. Appl. Phys.</i> 46 , 1186 (2007).	6	7	~22
<i>Adv. Mater.</i> 22 , 3311 (2010).	4	6	~18
OLED comprising a chlorine-functionalized anode	3	3	25.5

FIG. 21

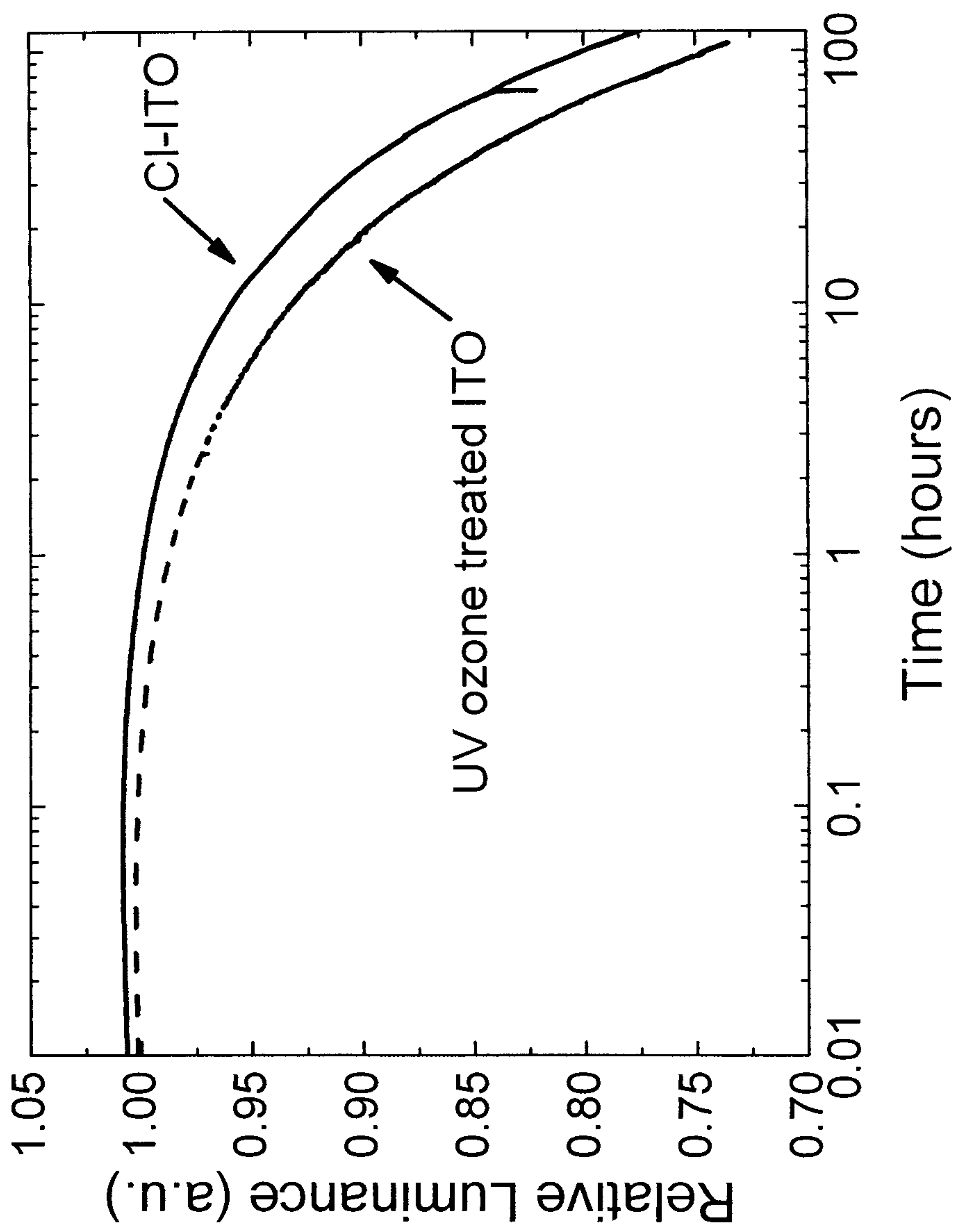


FIG. 22

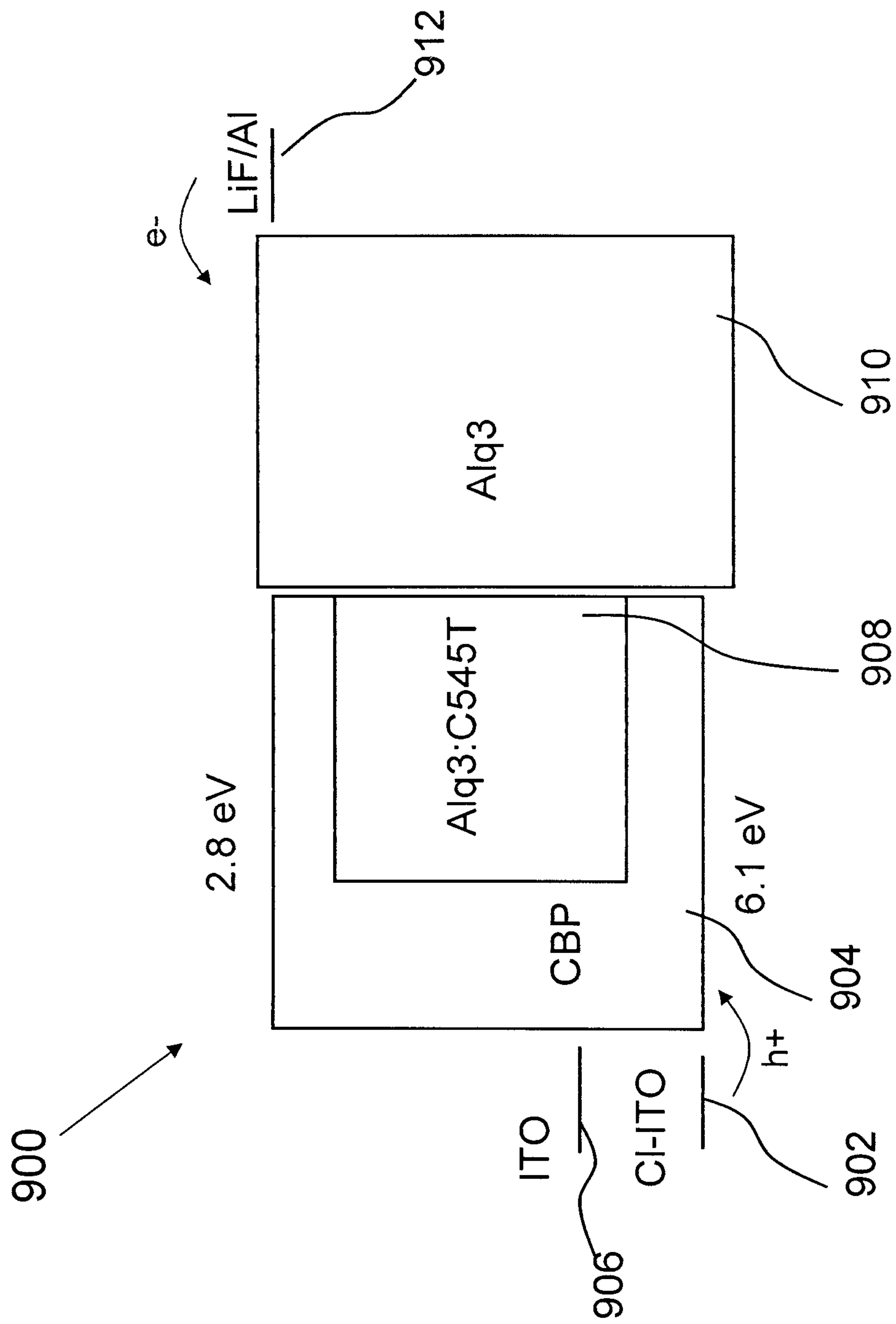


FIG. 23

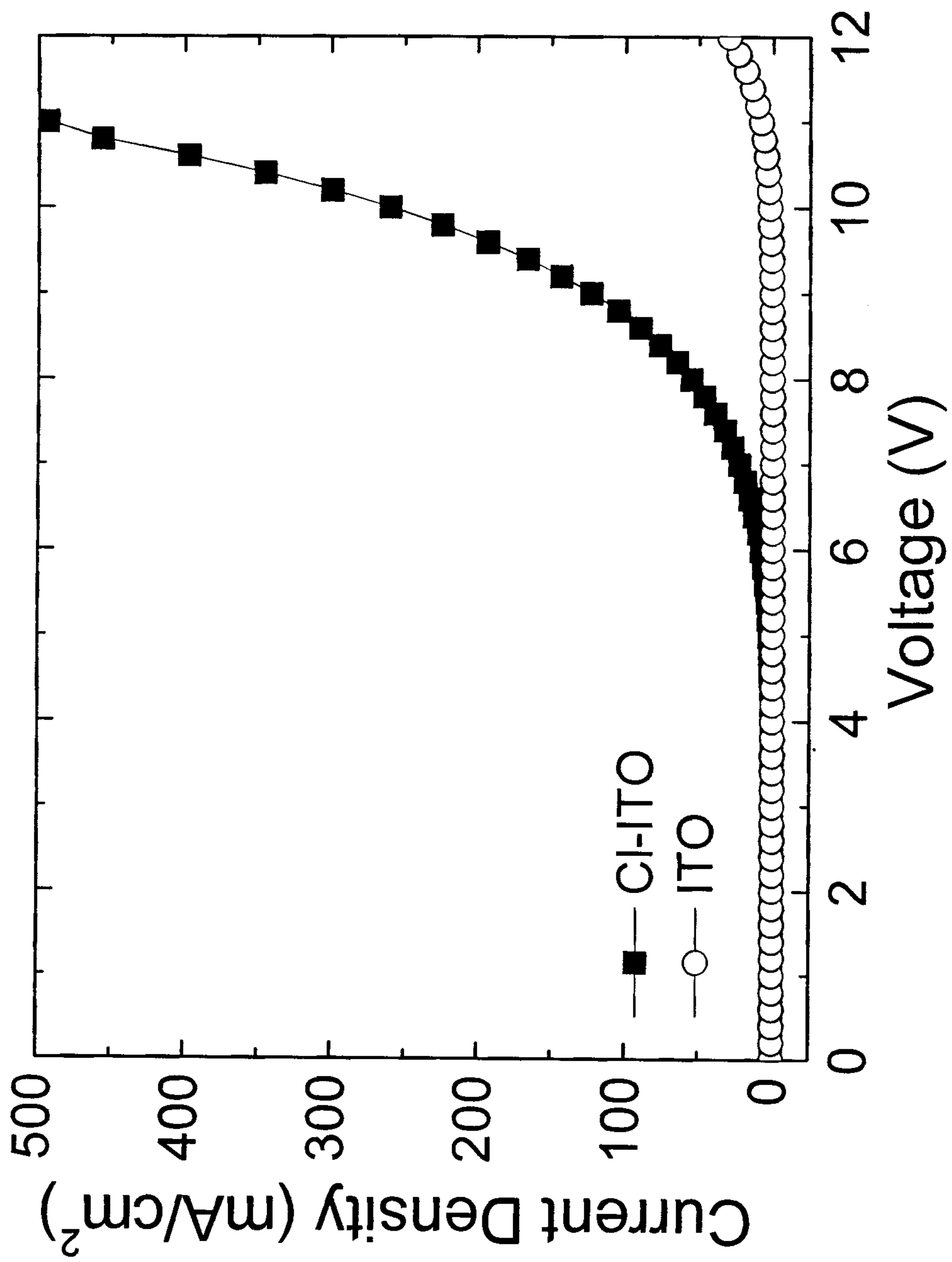


FIG. 24

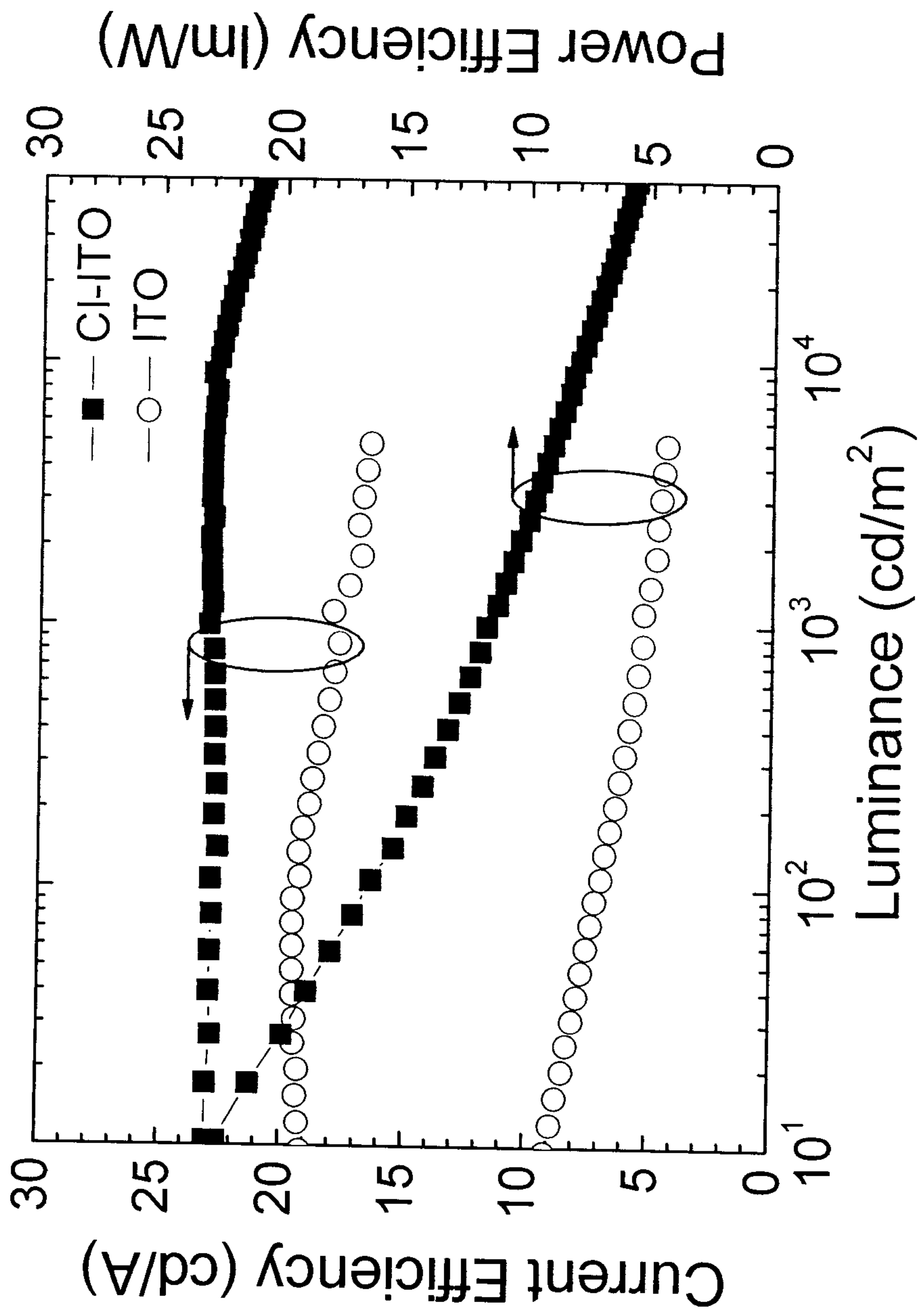


FIG. 25

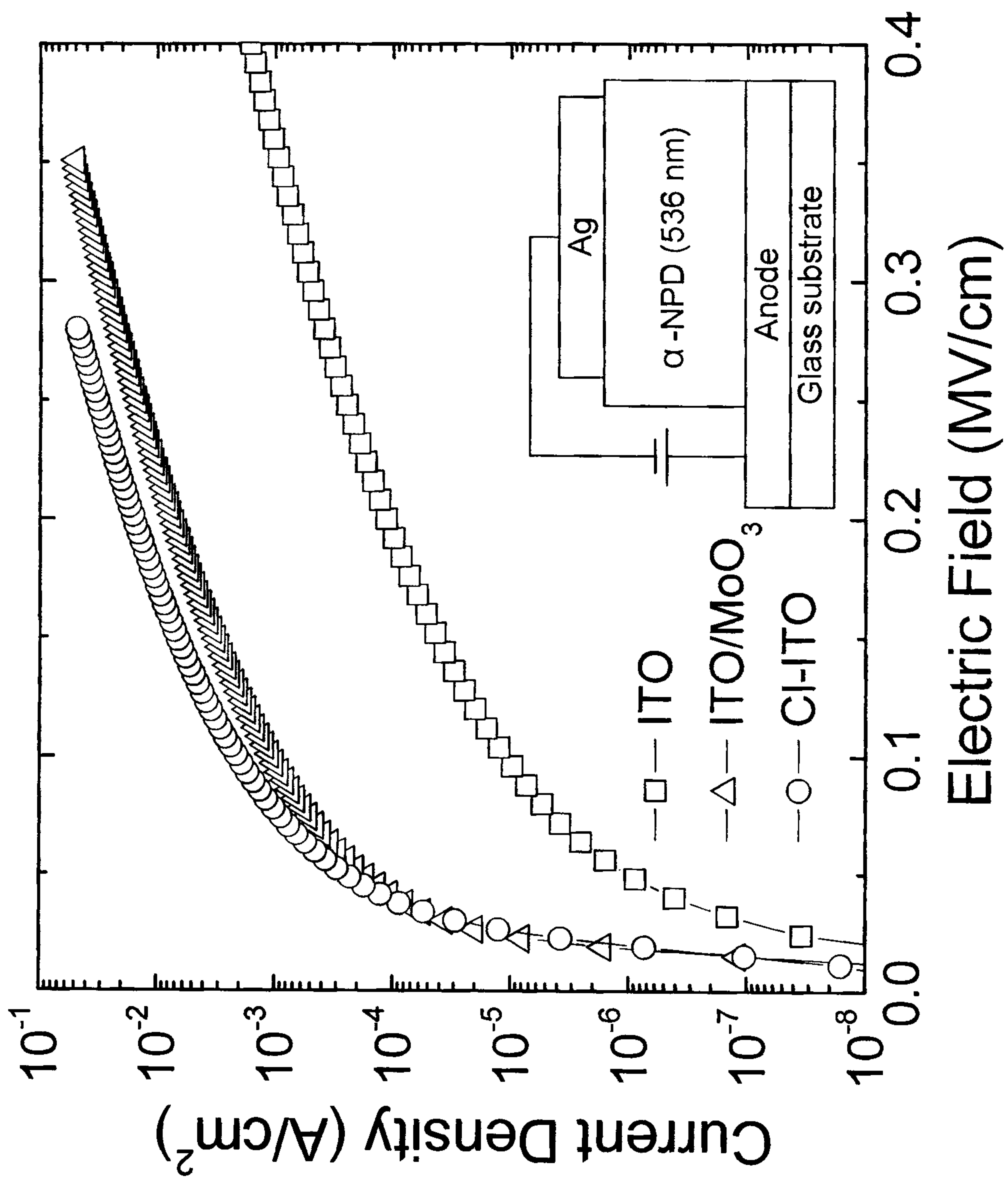


FIG. 26

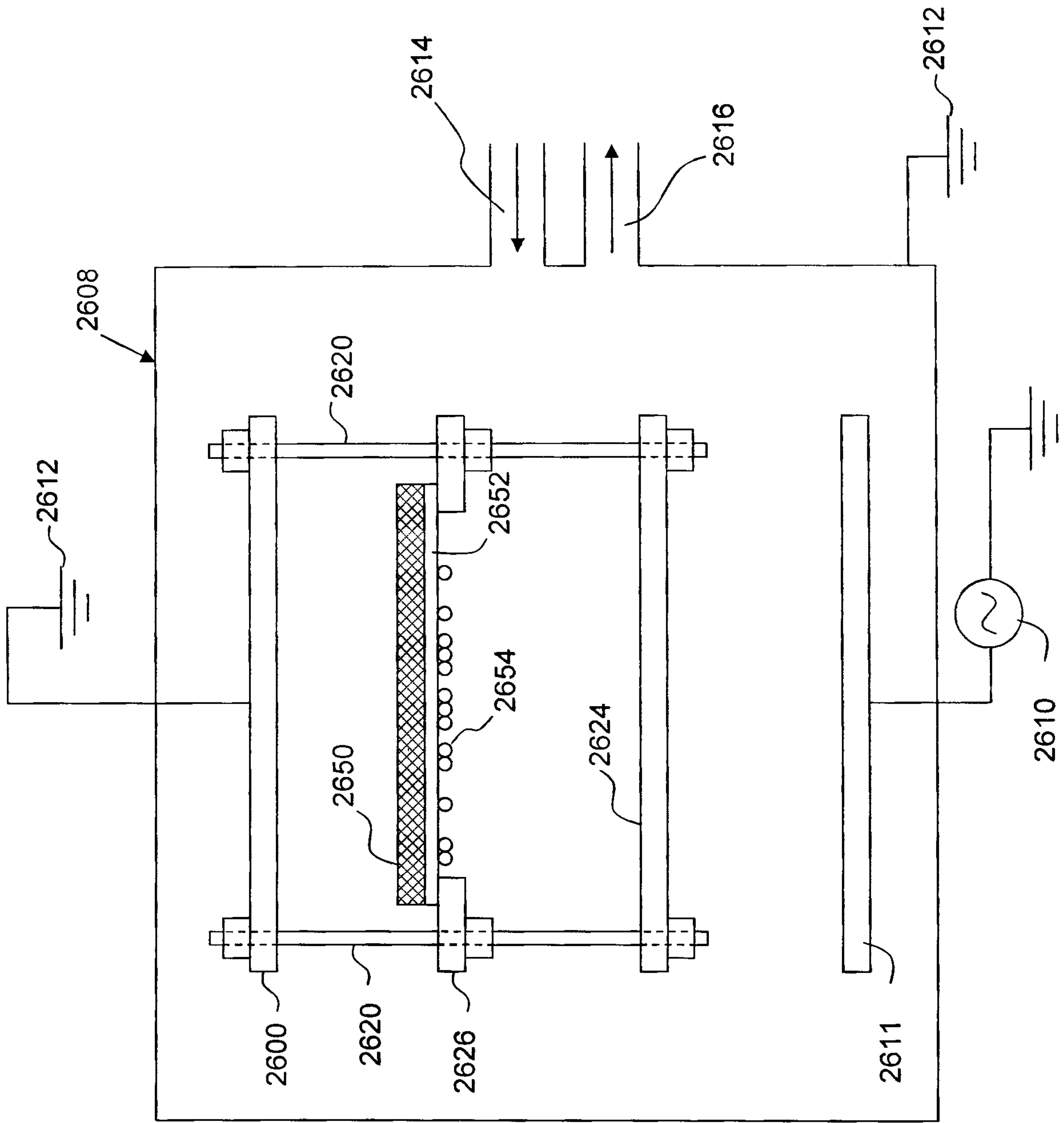


FIG. 27

