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(54) **PHOTOELECTRIC CONVERSION MATERIAL CONTAINING FULLERENE DERIVATIVE**

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(57) **ABSTRACT**

The present invention provides a photoelectric conversion material comprising a fullerene derivative represented by the formula  $C_{60}(R^1)_5(R^2)$ , wherein each  $R^1$  independently represents an organic group having a substituent; and  $R^2$  represents a hydrogen atom or a substituted or unsubstituted  $C_1-C_{30}$  hydrocarbon group. Further, the present invention also provides a photoelectric conversion device having a self-assembled monomolecular film of the photoelectric conversion material, and a solar cell having the photoelectric conversion device.

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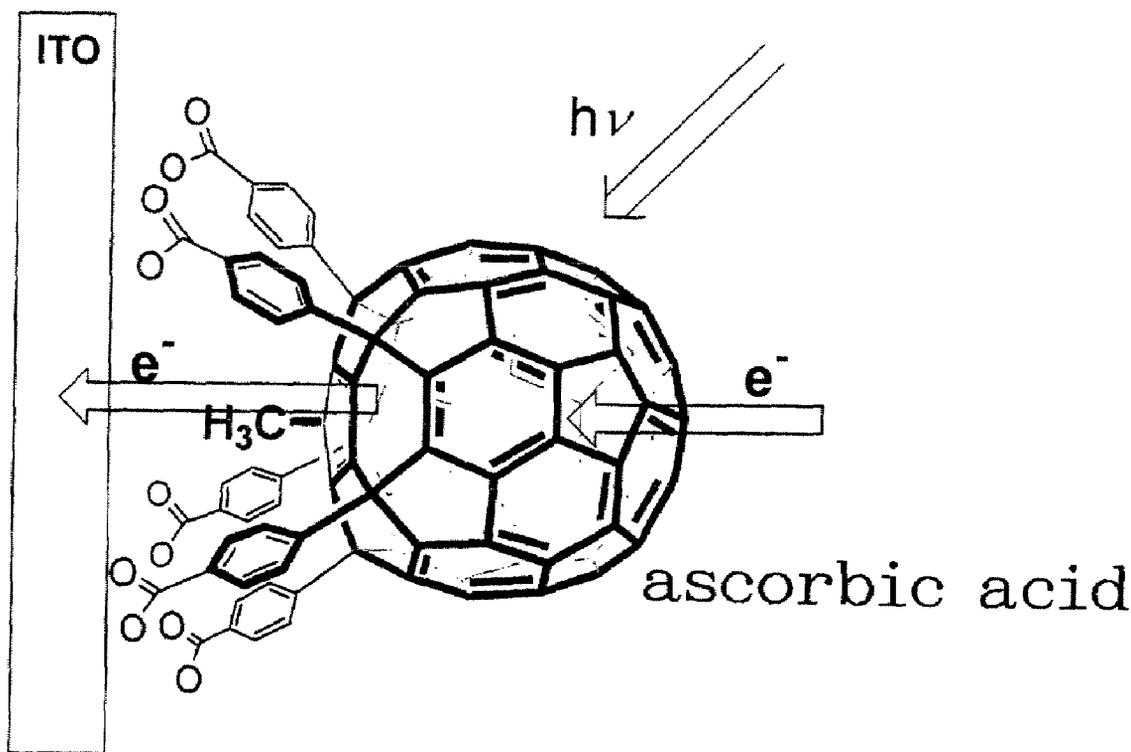
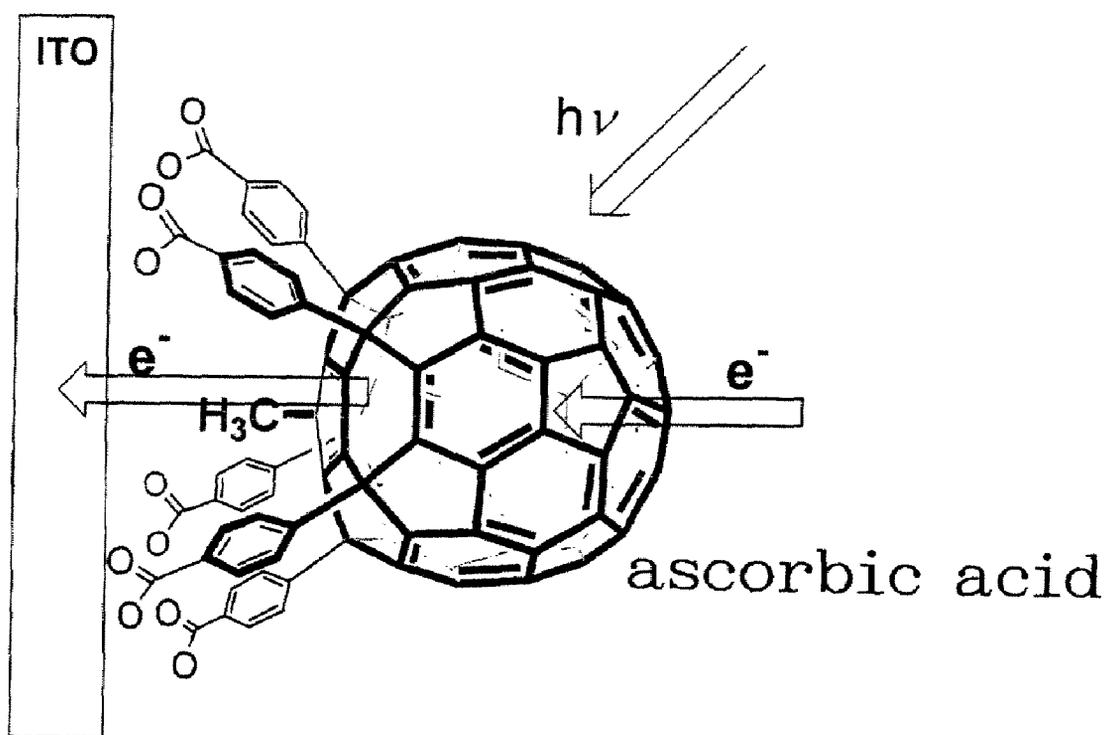


Figure 1



**PHOTOELECTRIC CONVERSION  
MATERIAL CONTAINING FULLERENE  
DERIVATIVE**

TECHNICAL FIELD

**[0001]** The present invention relates to a photoelectric conversion material comprising a fullerene derivative, a photoelectric conversion device having a self-assembled monomolecular film of the photoelectric conversion material, and a solar cell having the photoelectric conversion device.

BACKGROUND ART

**[0002]** Since the method for synthesizing a carbon cluster (hereinafter also referred to as "fullerene"), in which carbon atoms are arranged to form a spherical shape or a rugby ball shape, was established, fullerene has been energetically studied. As a result, many fullerene derivatives have been synthesized.

**[0003]** In general, fullerene derivatives have a widely-extended  $\pi$  electron system. Further, characteristically, fullerene derivatives have a relatively small HOMO-LUMO gap (about 1.5-2.0 eV), and also have optical absorption property in a wide wavelength range and highly-efficient light-emitting property via Singlet-to-Triplet intersystem crossing. Further, fullerenes are constituted only by carbon atoms, and at the same time, exhibit multistep reversible redox reaction (6-electron reduction). Attributed to these properties, there are wide range of possibilities for application of fullerene derivatives. For example, it is thought that fullerene derivatives can be utilized for FET, organic EL, solar cells, catalysts, etc.

**[0004]** Regarding a photoelectric conversion device utilizing optical absorption property of fullerene metal complexes, studies of the development of artificial photosynthesis utilizing high electron acceptor ability of fullerenes have been reported. Specifically, there are the following reports: a wet solar cell comprising a monomolecular film prepared by molecules, which are joined via chemical bond using ferrocene (electron donor)-porphyrin (optical absorption center)-fullerene (electron acceptor) on a gold electrode [Eur. J. Org. Chem. 2445. (1999) (non-patent document 1)]; and a wet solar cell, wherein molecules in which fullerene metal complex and porphyrin are joined together are immobilized on an ITO electrode [J. Am. Chem. Soc. 127, 2380, (2005) (non-patent document 2)].

**[0005]** However, these solar cells have the following problems: it is complicated to synthesize a fullerene derivative to be used in a photoelectric conversion device of a solar cell; and desired properties cannot be sufficiently exerted.

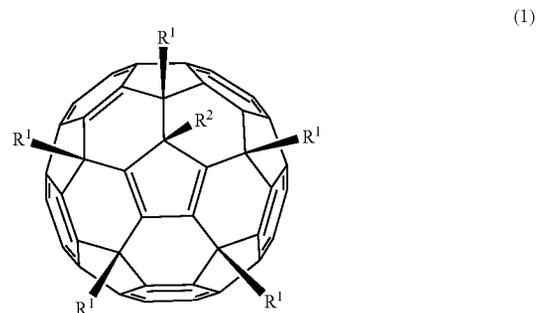
**[0006]** Under the above-described circumstances, for example, fullerene derivatives having very high quantum yield of photocurrent generation are desired. Moreover, fullerene derivatives, which have very high quantum yield of photocurrent generation, and which can be easily synthesized, are desired. In addition, solar cells having high power generation efficiency are desired.

DISCLOSURE OF THE INVENTION

**[0007]** The present inventors found fullerene derivatives having high quantum yield of photocurrent generation among fullerene derivatives which can be relatively easily synthesized, and completed the present invention based on this finding. The present invention provides a photoelectric conversion material comprising a fullerene derivative as described below, a photoelectric conversion device having a

self-assembled monomolecular film of the photoelectric conversion material, and a solar cell having the photoelectric conversion device.

[1] A photoelectric conversion material comprising a fullerene derivative represented by the following formula (1):

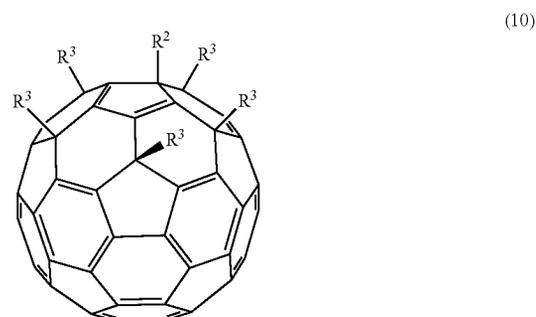


wherein: each  $R^1$  independently represents a  $C_1$ - $C_{30}$  hydrocarbon group, a  $C_1$ - $C_{30}$  alkoxy group, a  $C_6$ - $C_{30}$  aryloxy group, an amino group, a silyl group, an alkylthio group ( $-\text{SY}^1$ : in the formula,  $Y^1$  represents a substituted or unsubstituted  $C_1$ - $C_{30}$  alkyl group), an arylthio group ( $-\text{SY}^2$ : in the formula,  $Y^2$  represents a substituted or unsubstituted  $C_6$ - $C_{18}$  aryl group), an alkylsulfonyl group ( $-\text{SO}_2\text{Y}^3$ : in the formula,  $Y^3$  represents a substituted or unsubstituted  $C_1$ - $C_{30}$  alkyl group), or an arylsulfonyl group ( $-\text{SO}_2\text{Y}^4$ : in the formula,  $Y^4$  represents a substituted or unsubstituted  $C_6$ - $C_{18}$  aryl group), which has a carboxylic acid group, a phosphate group, a phosphonate group or  $-\text{SiO}_3$ ; and  $R^2$  represents a hydrogen atom or a substituted or unsubstituted  $C_1$ - $C_{30}$  hydrocarbon group.

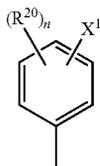
**[0008]** In item [1], it is preferred that each  $R^1$  is independently an organic group comprising a carboxylic acid group.

[2] The photoelectric conversion material according to item [1], wherein: each  $R^1$  independently represents a  $C_1$ - $C_{30}$  alkyl group, a  $C_2$ - $C_{30}$  alkenyl group, a  $C_2$ - $C_{30}$  alkynyl group, a  $C_4$ - $C_{30}$  alkyldienyl group, a  $C_6$ - $C_{18}$  aryl group, a  $C_7$ - $C_{30}$  alkylaryl group, a  $C_7$ - $C_{30}$  arylalkyl group, a  $C_4$ - $C_{30}$  cycloalkyl group or a  $C_4$ - $C_{30}$  cycloalkenyl group, which has a carboxylic acid group, a phosphate group, a phosphonate group or  $-\text{SiO}_3$ ; and  $R^2$  represents a hydrogen atom or a  $C_1$ - $C_{30}$  alkyl group.

[3] A photoelectric conversion material comprising a fullerene derivative represented by the following formula (10):



wherein:  $R^2$  represents a hydrogen atom or a substituted or unsubstituted  $C_1$ - $C_{30}$  hydrocarbon group; and each  $R^3$  is independently a group represented by the following formula (A):

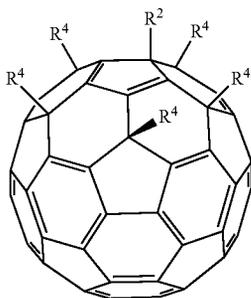


(A)

wherein:  $X^1$  represents a carboxylic acid group, a phosphate group, a phosphonate group or  $-\text{SiO}_3$ ; M represents a metal atom; each  $R^{20}$  independently represents an organic group; and n is an integer from 0 to 4.

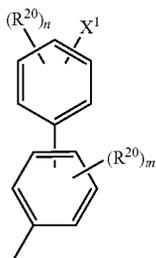
[0009] In item [3]: it is preferred that each  $X^1$  independently represents a carboxylic acid group; n is preferably 0; and  $X^1$  is preferably at the para position.

[4] A photoelectric conversion material comprising a fullerene derivative represented by the following formula (11):



(11)

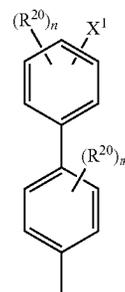
wherein:  $R^2$  represents a hydrogen atom or a substituted or unsubstituted  $C_1$ - $C_{30}$  hydrocarbon group; each  $R^4$  is independently a group represented by the following formula (B):



(B)

wherein:  $X^1$  represents a carboxylic acid group, a phosphate group, a phosphonate group or  $-\text{SiO}_3$ ; M represents a metal atom; each  $R^{20}$  independently represents an organic group; n is an integer from 0 to 4; and m is an integer from 0 to 4; and M represents a metal atom.

[0010] In item [4], the group represented by the formula (B) is preferably a group represented by the following formula (B1):



(B1)

wherein:  $X^1$  represents a carboxylic acid group, a phosphate group, a phosphonate group or  $-\text{SiO}_3$ ; M represents a metal atom; each  $R^{20}$  independently represents an organic group; n is an integer from 0 to 4; and m is an integer from 0 to 4.

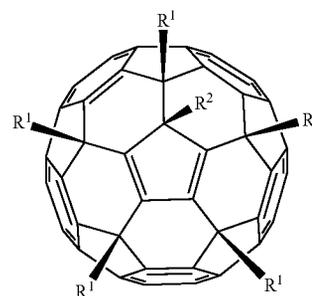
[0011] In the formula (B) or (B1): it is preferred that each  $X^1$  independently represents a carboxylic acid group; it is preferred that n and m are each independently 0; and  $X^1$  is preferably at the para position.

[5] A photoelectric conversion device having a self-assembled monomolecular film of the photoelectric conversion material according to any one of items [1] to [4].

[6] A photoelectric conversion device having an ITO electrode on which the self-assembled monomolecular film of the photoelectric conversion material according to any one of items [1] to [4] is formed.

[7] A solar cell having the photoelectric conversion device according to item [5] or [6].

[8] A photoelectric conversion material comprising a fullerene derivative represented by the following formula (1):



(1)

wherein: each  $R^1$  independently represents a  $C_1$ - $C_{30}$  hydrocarbon group, a  $C_1$ - $C_{30}$  alkoxy group, a  $C_6$ - $C_{30}$  aryloxy group, an amino group, a silyl group, an alkylthio group ( $-\text{SY}^1$ : in the formula,  $Y^1$  represents a substituted or unsubstituted  $C_1$ - $C_{30}$  alkyl group), an arylthio group ( $-\text{SY}^2$ : in the formula,  $Y^2$  represents a substituted or unsubstituted  $C_6$ - $C_{18}$  aryl group), an alkylsulfonyl group ( $-\text{SO}_2\text{Y}^3$ : in the formula,  $Y^3$  represents a substituted or unsubstituted  $C_1$ - $C_{30}$  alkyl group), or an arylsulfonyl group ( $-\text{SO}_2\text{Y}^4$ : in the formula,  $Y^4$  represents a substituted or unsubstituted  $C_6$ - $C_{18}$  aryl group), which has a thiol group or a disulfide group; and  $R^2$  represents a hydrogen atom or a substituted or unsubstituted  $C_1$ - $C_{30}$  hydrocarbon group.

[0012] In item [8], it is preferred that each  $R^1$  is independently an organic group comprising a carboxylic acid group.

[9] The photoelectric conversion material according to item [8], wherein: each  $R^1$  independently represents a  $C_1$ - $C_{30}$  alkyl group, a  $C_1$ - $C_{30}$  alkenyl group, a  $C_2$ - $C_{30}$  alkynyl group, a

$C_4$ - $C_{30}$  alkyldienyl group, a  $C_6$ - $C_{18}$  aryl group, a  $C_7$ - $C_{30}$  alkylaryl group, a  $C_1$ - $C_{30}$  arylalkyl group, a  $C_4$ - $C_{30}$  cycloalkyl group or a  $C_4$ - $C_{30}$  cycloalkenyl group, which has a thiol group or a disulfide group; and  $R^2$  represents a hydrogen atom or a  $C_1$ - $C_{30}$  alkyl group.

[10] A photoelectric conversion device having a self-assembled monomolecular film of the photoelectric conversion material according to item [8] or [9].

[11] A photoelectric conversion device having a gold electrode on which the self-assembled monomolecular film of the photoelectric conversion material according to item [8] or [9] is formed.

[12] A solar cell having the photoelectric conversion device according to item [10] or [11].

[0013] When using the fullerene derivative according to the preferred embodiment of the present invention, for example, a photoelectric conversion material having very high quantum yield of photocurrent generation can be provided. Moreover, for example, a photoelectric conversion material having very high quantum yield of photocurrent generation, which comprises a fullerene derivative that can be easily synthesized, can be provided. The photoelectric conversion device according to the preferred embodiment of the present invention has high quantum yield. Furthermore, the solar cell according to the preferred embodiment of the present invention can efficiently generate electric power, and it can be produced at a lower cost.

#### BRIEF DESCRIPTION OF THE DRAWINGS

[0014] FIG. 1 shows a mechanism of photoelectric conversion using a photoelectric conversion device.

#### BEST MODE FOR CARRYING OUT THE INVENTION

##### 1. Fullerene Derivative Included in the Photoelectric Conversion Material of the Present Invention

[0015] As described above, the fullerene derivative obtained using the production method of the present invention is a fullerene derivative represented by the formula:  $C_{60}(R^1)_5(R^2)$ , wherein: each  $R^1$  independently represents an organic group having a substituent; and  $R^2$  represents a hydrogen atom or a substituted or unsubstituted  $C_1$ - $C_{30}$  hydrocarbon group. Specifically, it is a fullerene derivative represented by the above-described formula (1).

[0016] In formula (1), each  $R^1$  independently represents an organic group having a substituent. Among such organic groups, it is preferred that each  $R^1$  independently represents a hydrogen atom, a substituted or unsubstituted  $C_1$ - $C_{30}$  hydrocarbon group, a substituted or unsubstituted  $C_1$ - $C_{30}$  alkoxy group, a substituted or unsubstituted  $C_6$ - $C_{30}$  aryloxy group, a substituted or unsubstituted amino group, a substituted or unsubstituted silyl group, a substituted or unsubstituted alkythio group ( $-SY^1$ : in the formula,  $Y^1$  represents a substituted or unsubstituted  $C_1$ - $C_{30}$  alkyl group), a substituted or unsubstituted arylthio group ( $-SY^2$ : in the formula,  $Y^2$  represents a substituted or unsubstituted  $C_6$ - $C_{15}$  aryl group), a substituted or unsubstituted alkylsulfonyl group ( $-SO_2Y^3$ : in the formula,  $Y^3$  represents a substituted or unsubstituted  $C_1$ - $C_{30}$  alkyl group), or a substituted or unsubstituted arylsulfonyl group ( $-SO_2Y^4$ : in the formula,  $Y^4$  represents a substituted or unsubstituted  $C_6$ - $C_1$  aryl group).

[0017]  $R^1$  can have one or more substituents selected from the group consisting of a carboxylic acid group, a phosphate group, a phosphonate group,  $-SiO_3$ , a thiol group, a disulfide group, an ester group, an amide group, an alkyne group, a trimethylsilyl group, a trimethylsilylethynyl group, an aryl

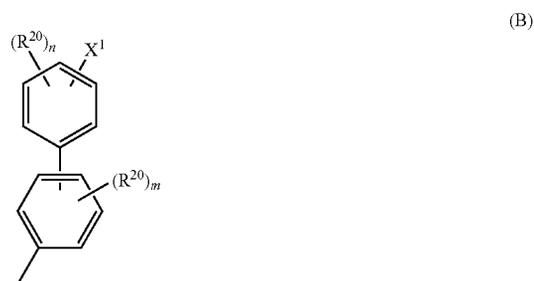
group, an amino group, a phosphonyl group, a thio group, a carbonyl group, a nitro group, a sulfo group, an imino group, a halogeno group, and an alkoxy group. Among these substituents, it is preferred that  $R^1$  has one or more substituents selected from the group consisting of a carboxylic acid group, a phosphate group, a phosphonate group,  $-SiO_3$ , a thiol group, and a disulfide group.

[0018] In formula (1),  $R^2$  represents a hydrogen atom or a  $C_1$ - $C_{30}$  hydrocarbon group, preferably represents a hydrogen atom or a  $C_1$ - $C_{30}$  alkyl group, and more preferably represents a methyl group.

[0019] Further, when the fullerene derivative represented by formula (1) is used in an ITO (indium tin oxide) electrode, in formula (1), it is preferred that each  $R^1$  independently represents a  $C_1$ - $C_{30}$  hydrocarbon group, a  $C_1$ - $C_{30}$  alkoxy group, a  $C_6$ - $C_{30}$  aryloxy group, an amino group, a silyl group, an alkythio group ( $-SY^1$ : in the formula,  $Y^1$  represents a substituted or unsubstituted  $C_1$ - $C_{30}$  alkyl group), an arylthio group ( $-SY^2$ : in the formula,  $Y^2$  represents a substituted or unsubstituted  $C_6$ - $C_{18}$  aryl group), an alkylsulfonyl group ( $-SO_2Y^3$ : in the formula,  $Y^3$  represents a substituted or unsubstituted  $C_1$ - $C_{30}$  alkyl group), or an arylsulfonyl group ( $-SO_2Y^4$ : in the formula,  $Y^4$  represents a substituted or unsubstituted  $C_6$ - $C_1$  aryl group), which has a carboxylic acid group, a phosphate group, a phosphonate group or  $-SiO_3$ , and it is more preferred that each  $R^1$  independently represents a  $C_1$ - $C_{30}$  alkyl group, a  $C_2$ - $C_{30}$  alkenyl group, a  $C_2$ - $C_{30}$  alkylnyl group, a  $C_4$ - $C_{30}$  alkyldienyl group, a  $C_6$ - $C_{18}$  aryl group, a  $C_7$ - $C_{30}$  alkylaryl group, a  $C_7$ - $C_{30}$  arylalkyl group, a  $C_4$ - $C_{30}$  cycloalkyl group or a  $C_4$ - $C_{30}$  cycloalkenyl group, which has a carboxylic acid group, a phosphate group, a phosphonate group or  $-SiO_3$ . Moreover, in formula (1), it is preferred that each  $R^1$  is independently a group represented by the following formula:



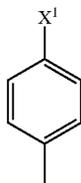
wherein:  $X^1$  represents a carboxylic acid group, a phosphate group, a phosphonate group or  $-SiO_3$ ;  $M$  represents a metal atom; each  $R^{20}$  independently represents an organic group; and  $n$  is an integer from 0 to 4, or a group represented by the following formula:



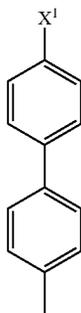
wherein:  $X^1$  represents a carboxylic acid group, a phosphate group, a phosphonate group or  $-SiO_3$ ;  $M$  represents a metal atom; each  $R^{20}$  independently represents an organic group;  $n$  is an integer from 0 to 4; and  $m$  is an integer from 0 to 4. In this

regard, in formulae (A) and (B), both  $n$  and  $m$  are preferably 0. Further,  $R^{20}$  is not particularly limited as long as it is an organic group, but is preferably a  $C_1$ - $C_{30}$  hydrocarbon group.

**[0020]** The group represented by formula (A) is particularly preferably a group represented by the following formula:



wherein each  $X^1$  independently represents a carboxylic acid group, a phosphate group, a phosphonate group,  $-\text{SiO}_3$ , a thiol group, or a disulfide group. The group represented by formula (B) is particularly preferably a group represented by the following formula:



wherein each  $X^1$  independently represents a carboxylic acid group, a phosphate group, a phosphonate group,  $-\text{SiO}_3$ , a thiol group, or a disulfide group.

**[0021]** In the present specification, the hydrocarbon group of the “ $C_1$ - $C_{30}$  hydrocarbon group” may be a saturated or unsaturated acyclic group or a saturated or unsaturated cyclic group. When the  $C_1$ - $C_{30}$  hydrocarbon group is acyclic, it may be linear or branched. The “ $C_1$ - $C_{30}$  hydrocarbon group” includes  $C_1$ - $C_{30}$  alkyl group,  $C_2$ - $C_{30}$  alkenyl group,  $C_2$ - $C_{30}$  alkynyl group,  $C_4$ - $C_{30}$  alkyldienyl group,  $C_6$ - $C_{18}$  aryl group,  $C_7$ - $C_{30}$  alkylaryl group,  $C_7$ - $C_{30}$  arylalkyl group,  $C_4$ - $C_{30}$  cycloalkyl group,  $C_4$ - $C_{30}$  cycloalkenyl group, and ( $C_3$ - $C_{10}$  cycloalkyl)  $C_1$ - $C_{10}$  alkyl group.

**[0022]** In the present specification, the “ $C_1$ - $C_{30}$  alkyl group” is preferably  $C_1$ - $C_{10}$  alkyl group, and more preferably  $C_1$ - $C_6$  alkyl group. Examples of alkyl groups include, but are not limited to, methyl, ethyl, propyl, isopropyl, n-butyl, sec-butyl, tert-butyl, pentyl, hexyl, and dodecanyl.

**[0023]** In the present specification, the “ $C_2$ - $C_{30}$  alkenyl group” is preferably  $C_2$ - $C_1$ , alkenyl group, and more preferably  $C_2$ - $C_6$  alkenyl group. Examples of alkenyl groups include, but are not limited to, vinyl, allyl, propenyl, isopropenyl, 2-methyl-1-propenyl, 2-methylallyl, and 2-butenyl.

**[0024]** In the present specification, the “ $C_{10}$ - $C_{10}$  alkynyl group” is preferably  $C_2$ - $C_{10}$  alkynyl group, and more prefer-

ably  $C_1$ - $C_6$  alkynyl group. Examples of alkynyl groups include, but are not limited to, ethynyl, propynyl, and butynyl.

**[0025]** In the present specification, the “ $C_4$ - $C_{30}$  alkyldienyl group” is preferably  $C_4$ - $C_{10}$  alkyldienyl group, and more preferably  $C_4$ - $C_6$  alkyldienyl group. Examples of alkyldienyl groups include, but are not limited to, 1,3-butadienyl.

**[0026]** In the present specification, the “ $C_6$ - $C_{18}$  aryl group” is preferably  $C_6$ - $C_{10}$  aryl group. Examples of aryl groups include, but are not limited to, phenyl, 1-naphthyl, 2-naphthyl, indenyl, biphenyl, anthryl, and phenanthryl.

**[0027]** In the present specification, the “ $C_7$ - $C_{30}$  alkylaryl group” is preferably  $C_7$ - $C_{12}$  alkylaryl group. Examples of alkylaryl groups include, but are not limited to, o-tolyl, m-tolyl, p-tolyl, 2,3-xylyl, 2,4-xylyl, 2,5-xylyl, o-cumenyl, m-cumenyl, p-cumenyl, and mesityl.

**[0028]** In the present specification, the “ $C_7$ - $C_{30}$  arylalkyl group” is preferably  $C_7$ - $C_{12}$  arylalkyl group. Examples of arylalkyl groups include, but are not limited to, benzyl, phenethyl, diphenylmethyl, triphenylmethyl, 1-naphthylmethyl, 2-naphthylmethyl, 2,2-diphenylethyl, 3-phenylpropyl, 4-phenylbutyl, and 5-phenylpentyl.

**[0029]** In the present specification, the “ $C_4$ - $C_{30}$  cycloalkyl group” is preferably  $C_4$ - $C_{10}$  cycloalkyl group. Examples of cycloalkyl groups include, but are not limited to, cyclopropyl, cyclobutyl, cyclopentyl, and cyclohexyl.

**[0030]** In the present specification, the “ $C_4$ - $C_{30}$  cycloalkenyl group” is preferably  $C_4$ - $C_{10}$  cycloalkenyl group. Examples of cycloalkenyl groups include, but are not limited to, cyclopropenyl, cyclobutenyl, cyclopentenyl, and cyclohexenyl.

**[0031]** In the present specification, the “ $C_1$ - $C_{30}$  alkoxy group” is preferably  $C_1$ - $C_{10}$  alkoxy group, and more preferably  $C_1$ - $C_6$  alkoxy group. Examples of alkoxy groups include, but are not limited to, methoxy, ethoxy, propoxy, butoxy, and pentyloxy.

**[0032]** In the present specification, the “ $C_6$ - $C_{30}$  aryloxy group” is preferably  $C_6$ - $C_{10}$  aryloxy group. Examples of aryloxy groups include, but are not limited to, phenyloxy, naphthyloxy, and biphenyloxy.

**[0033]** In the present specification, in “alkylthio group ( $-\text{SY}^1$ : in the formula,  $Y^1$  is a substituted or unsubstituted  $C_1$ - $C_{30}$  alkyl group)” and “alkylsulfonyl group ( $-\text{SO}_2\text{Y}^3$ : in the formula,  $Y^3$  is a substituted or unsubstituted  $C_1$ - $C_{30}$  alkyl group)”,  $Y^1$  and  $Y^3$  are preferably  $C_1$ - $C_{10}$  alkyl group, and more preferably  $C_1$ - $C_6$  alkyl group. Examples of alkyl groups include, but are not limited to, methyl, ethyl, propyl, isopropyl, n-butyl, sec-butyl, tert-butyl, pentyl, hexyl, and dodecanyl.

**[0034]** In the present specification, in “arylthio group ( $-\text{SY}^2$ : in the formula,  $Y^2$  is a substituted or unsubstituted  $C_6$ - $C_{18}$  aryl group)” and “arylsulfonyl group ( $-\text{SO}_2\text{Y}^4$ : in the formula,  $Y^4$  is a substituted or unsubstituted  $C_6$ - $C_1$  aryl group)”,  $Y^2$  and  $Y^4$  are preferably  $C_6$ - $C_{10}$  aryl group. Examples of aryl groups include, but are not limited to, phenyl, 1-naphthyl, 2-naphthyl, indenyl, biphenyl, anthryl, and phenanthryl.

2. Method for Producing a Fullerene Derivative Included in the Photoelectric Conversion Material of the Present Invention

**[0035]** The method for producing a fullerene derivative included in the photoelectric conversion material of the present invention is not particularly limited. However, for example, a fullerene derivative can be synthesized by react-

ing: a fullerene; a halogenated organic compound (A) represented by the following formula (2):



wherein  $R^5$  represents an organic group, and  $X^2$  represents a halogen atom; a Grignard reagent (B) represented by the following formula (3):



wherein  $R^6$  represents an organic group, and  $X^3$  represents a halogen atom; and an organocopper reagent (C) prepared from a monovalent or divalent copper compound.

### 2.1. Fullerene

**[0036]** Examples of fullerenes to be used in the method for producing the fullerene derivative of the present invention include fullerene  $C_{60}$  (so-called "buckminsterfullerene").

### 2.2. Halogenated Organic Compound (A)

**[0037]** The halogenated organic compound (A) to be used in the production method of the present invention is represented by the above-described formula (2).

**[0038]** In formula (2),  $R^5$  is not particularly limited as long as it is an organic group. However, for example,  $R^5$  represents a substituted or unsubstituted  $C_1$ - $C_2$ (hydrocarbon group, a substituted or unsubstituted  $C_1$ - $C_{20}$  alkoxy group, a substituted or unsubstituted  $C_6$ - $C_{20}$  aryloxy group, a substituted or unsubstituted amino group, a substituted or unsubstituted silyl group, a substituted or unsubstituted alkylthio group ( $-SY^1$ : in the formula,  $Y^1$  represents a substituted or unsubstituted  $C_1$ - $C_{20}$  alkyl group), a substituted or unsubstituted arylthio group ( $-SY^2$ : in the formula,  $Y^2$  represents a substituted or unsubstituted  $C_6$ - $C_{18}$  aryl group), a substituted or unsubstituted alkylsulfonyl group ( $-SO_2Y^3$ : in the formula,  $Y^3$  represents a substituted or unsubstituted  $C_1$ - $C_{20}$  alkyl group), or a substituted or unsubstituted arylsulfonyl group ( $-SO_2Y^4$ : in the formula,  $Y^4$  represents a substituted or unsubstituted  $C_6$ - $C_{18}$  aryl group).

**[0039]** More specifically,  $R^5$  may have substituents comprising functional groups such as an ester group, a carboxyl group, an amide group, an alkyne group, a trimethylsilyl group, a trimethylsilylethynyl group, an aryl group, an amino group, a phosphonyl group, a thio group, a carbonyl group, a nitro group, a sulfo group, an imino group, a halogeno group, and an alkoxy group. In terms of easiness of synthesis of the halogenated organic compound,  $R^5$  preferably comprises one or more functional groups selected from the group consisting of an ester group, an amide group, an alkyne group, a trimethylsilyl group and an aryl group. In this case, when 2 or more functional groups are included in  $R^5$ , they may be the same or different.

**[0040]** In formula (2),  $X^2$  represents a halogen atom. Among halogen atoms,  $X^2$  is preferably Cl, Br or I.

### 2.3. Grignard Reagent (B)

**[0041]** The Grignard reagent (B) to be used in the production method of the present invention is represented by the above-described formula (3).

**[0042]** In formula (3),  $R^6$  is not particularly limited as long as it is an organic group having an inactive substituent by which the Grignard reagent can be adjusted. Examples of such substituents include an alkyl group, an alkenyl group, an alkynyl group, an aralkyl group, and an aryl group.

**[0043]** In formula (3),  $X^3$  represents a halogen atom. Among halogen atoms,  $X^3$  is preferably Cl, Br or I.

### 2.4. Organocopper Reagent (C)

**[0044]** The organocopper reagent (C) to be used in the production method of the present invention is not particularly limited as long as it is prepared from a monovalent or divalent copper compound. Among them, in terms of easiness of purification and higher purity,  $CuBr \cdot S(CH_3)_2$  is preferably used as the organocopper reagent.

**[0045]** Further, according to circumstances, for example, in order to stabilize the organocopper reagent and improve solubility, an additive such as N,N-dimethylimidazolidinone (DMI) and N-butylpyrrolidone (NBT) can be suitably used.

### 2.5. Mixing Ratio, etc.

**[0046]** In general, the halogenated organic compound (A), the Grignard reagent (B) and the organocopper reagent (C) are used in an amount of 5 to 50 equivalents, and preferably 10 to 20 equivalents of a fullerene.

**[0047]** Further, in the production method of the present invention, the mixing ratio (molar ratio) of the halogenated organic compound (A) to the Grignard reagent (B) is preferably 1:0.8 to 1:1, and the mixing ratio (molar ratio) of the Grignard reagent (B) to the organocopper reagent (C) is preferably 1:0.8 to 0.8:1.

**[0048]** In order to synthesize a fullerene derivative with a high purity, it is preferred that slightly excessive amounts of the halogenated organic compound and the organocopper reagent are used with respect to the Grignard reagent.

### 2.5. Reaction Conditions

**[0049]** Reaction of the fullerene, the halogenated organic compound (A), the Grignard reagent (B) and the organocopper reagent (C) in the production method of the fullerene derivative included in the photoelectric conversion material of the present invention is generally performed in an inert solvent such as toluene, tetrahydrofuran, dichlorobenzene, or a mixture thereof.

**[0050]** The reaction is preferably performed at a temperature in the range from  $-70^\circ C.$  to  $70^\circ C.$ , and more preferably in the range from  $-50^\circ C.$  to  $50^\circ C.$

**[0051]** Further, reaction time depends on a solvent to be used, temperature, etc. In general, the reaction is performed for about several minutes to 5 hours, and preferably for about 10 minutes to 4 hours.

**[0052]** Termination of synthesis reaction of the fullerene derivative included in the photoelectric conversion material of the present invention can be carried out by adding an ammonium chloride solution or the like to the reaction system.

### 2.6. Isolation of Fullerene Derivative

**[0053]** The method for isolating the fullerene derivative from the synthesis reaction system of the fullerene derivative included in the photoelectric conversion material of the present invention is not particularly limited. For example, a reaction solution is directly passed through a silica gel column to remove by-products such as inorganic substances. According to need, isolated substances are further purified by

means of HPLC, usual column chromatography, etc., to improve purity of the fullerene derivative.

### 2.7. Conversion of Substituent Added to Fullerene Skeleton

**[0054]** A substituent added to a fullerene skeleton by the above-described synthesis reaction of the fullerene derivative of the present invention can be converted.

**[0055]** For example, a fullerene derivative to which a carboxyl group is added can be obtained by: adding a base such as NaH and NaOH to a fullerene derivative to which an ester group is added as a substituent, which is obtained by the above-described synthesis reaction of the fullerene derivative; and replacing the ester group with a carboxyl group.

### 3. Photoelectric Conversion Device of the Present Invention

**[0056]** The photoelectric conversion device of the present invention has a structure in which a self-assembled monomolecular film of the aforementioned photoelectric conversion material is formed on a support.

**[0057]** As the support to be used for the photoelectric conversion device of the present invention, a conductive material such as a metal plate, and a structure in which a conductive substance is provided to a nonconductive material such as a glass plate and a plastic film can be used. Examples of materials to be used for the support include metals (e.g., platinum, gold, silver, copper, aluminium, rhodium, and indium), conductive metal oxides (e.g., indium-tin composite oxide, and tin oxide doped with fluorine), and carbon. The thickness of the support is not particularly limited, but is preferably 0.3 mm to 5 mm.

**[0058]** Further, it is preferred that the support is substantially transparent. The term "substantially transparent" means that the light transmission rate is 10% or more. The rate is more preferably 50% or more, and most preferably 80% or more. In order to obtain a transparent support, it is preferred that a conductive layer consisting of a conductive metal oxide is provided to the surface of a glass plate or a plastic film. When using a transparent support, light incidence is preferably from the support side.

**[0059]** The surface resistance of the support is preferably  $50 \Omega/\text{cm}^2$  or less, and more preferably  $10 \Omega/\text{cm}^2$  or less.

**[0060]** A self-assembled film means a film in which a part of organic compounds constituting the film are bound to functional groups on the surface of a substrate. The self-assembled film has very few defects and has high orderliness, i.e., crystallinity. The self-assembled film can be relatively easily produced, and therefore it is easy to form the film on the substrate.

**[0061]** The self-assembled monomolecular film of the present invention is characterized in that a part of fullerene derivatives constituting the film are bound to the surface of a support such as an electrode.

**[0062]** The method for binding fullerene derivatives to the surface of a support is not particularly limited. For example, a solution of fullerene derivatives is prepared; a surface-treated substrate is immersed in the solution; and thereby the self-assembled monomolecular film of the fullerene derivatives is formed on the surface of the support. Alternatively, the monomolecular film can be formed without surface treatment.

**[0063]** Examples of supports to be used to obtain a material for the photoelectric conversion device of the present invention include a conductive support which is surface-treated so

that it has an electric charge that is opposite to that of the functional group of the fullerene derivative used. Preferred examples of supports include an ITO electrode in which ITO is deposited on a glass substrate, a gold electrode in which gold is deposited on a glass substrate, etc.

**[0064]** In order to perform a treatment to impart an anionic surface on a gold electrode, for example, the gold electrode is immersed in an ethanol solution of a compound, one terminus of which has a thiol site that binds to gold, and the other terminus of which has an anionic site, such as mercaptoethanesulfonic acid (MES). After that, the gold electrode is washed with water to remove unbound MES. When preparing a cationic surface, operation is performed as in the case of the electrode with the anionic surface, using a solution of a compound, one terminus of which has a thiol site, and the other terminus of which has a cationic site (e.g., mercaptoethylamine hydrochloride).

**[0065]** When using an ITO electrode as a substrate, the surface thereof can be treated so as to be anionic or cationic using the same technique as that applied to the gold electrode.

**[0066]** Thus, the self-assembled monomolecular film of the fullerene derivative is formed on the support by immersing the support, which is surface-treated so as to be anionic or cationic, in the aforementioned solution of the fullerene derivative, and thereafter, by washing the support to remove unbound fullerene derivative. In this way, the photoelectric conversion device having the self-assembled monomolecular film of the photoelectric conversion material can be obtained.

**[0067]** When the support on which the monomolecular film is formed is an ITO electrode, it is preferred that each  $R^1$  in the fullerene derivative represented by the above-described formula (1) included in the monomolecular film independently has a carboxylic acid group, a phosphate group, a phosphonate group or  $-\text{SiO}_3$ . It is more preferred that these substituents bind to the site of fullerene skeleton via  $\pi$  conjugated bond.

**[0068]** Further, when the support on which the monomolecular film is formed is a gold electrode, it is preferred that each  $R^1$  in the fullerene derivative represented by the above-described formula (1) included in the monomolecular film independently has a thiol group or a disulfide group. It is more preferred that these substituents bind to the site of fullerene skeleton via  $\pi$  conjugated bond.

**[0069]** In the photoelectric conversion device of the present invention, the monomolecular film is formed on the support. However, according to need, the device may have a multilayer structure, wherein the support is further laminated with other substances. In general, such a multilayer structure can be obtained by successively immersing the support in solutions of substances, each of which has an electric charge opposite to that of the outermost layer, according to a technique known as an alternating lamination method.

### 4. Solar Cell of the Present Invention

**[0070]** The solar cell of the present invention is not particularly limited as long as it is a solar cell comprising the above-described photoelectric conversion device. Examples thereof include a cell, wherein a charge transfer layer is formed on the monomolecular film of the photoelectric conversion device of the present invention, and an opposite electrode is further formed on the charge transfer layer.

**[0071]** As a charge transfer layer which the solar cell of the present invention has, a publicly-known charge transfer layer is used. For example, the charge transfer layer which the solar

cell of the present invention has is constituted by a disperse material of redox electrolytes. When the disperse material is a solution, it is called a liquid electrolyte. When the disperse material is dispersed in a polymer that is a solid at ordinary temperature, it is called a solid polyelectrolyte. When the disperse material is dispersed in a gel-like material, it is called a gel electrolyte. When a liquid electrolyte is used as the charge transfer layer, a solvent thereof to be used is electrochemically inactive. Examples thereof include acetonitrile, propylene carbonate and ethylene carbonate. Examples of redox electrolytes include  $I^-/I_3^-$  system,  $Br^-/Br_3^-$  system and quinone/hydroquinone system. These redox electrolytes can be obtained using a publicly-known method. For example, electrolytes of the  $I^-/I_3^-$  system can be obtained by mixing ammonium salt of iodine with iodine.

[0072] Further, specific examples of the charge transfer layers to be used in the present invention include a liquid electrolyte that is an aqueous solution of sodium sulfate in which ascorbic acid is dissolved.

[0073] The opposite electrode which the solar cell of the present invention has is not particularly limited as long as it has conductivity, and any conductive material can be used therefor. However, the electrode preferably has catalytic ability to allow oxidation of  $I_3^-$  ion, etc. and reduction reaction of other redox ions with a sufficient speed. Examples of such electrodes include a platinum electrode, an electrode in which platinization or platinum deposition is applied to the surface of a conductive material, rhodium metal, ruthenium metal, ruthenium oxide and carbon.

#### 5. Mechanism of Photoelectric Conversion Using the Photoelectric Conversion Device of the Present Invention

[0074] A mechanism of photoelectric conversion using the photoelectric conversion device of the present invention will be described below based on FIG. 1. In FIG. 1, as a specific example, a photoelectric conversion device in which a monomolecular film of a fullerene derivative is formed on an ITO electrode is described.

[0075] Initially, when optical energy ( $h\nu$ ) irradiated from outside is absorbed by the fullerene derivative, ascorbic acid which constitutes the charge transfer layer provides electron ( $e^-$ ) to the fullerene, and the electron ( $e^-$ ) entered into LUMO of the fullerene derivative provides electron to ITO. As a result, anode current is generated, and current flows through a circuit connected to the solar cell.

#### EXAMPLES

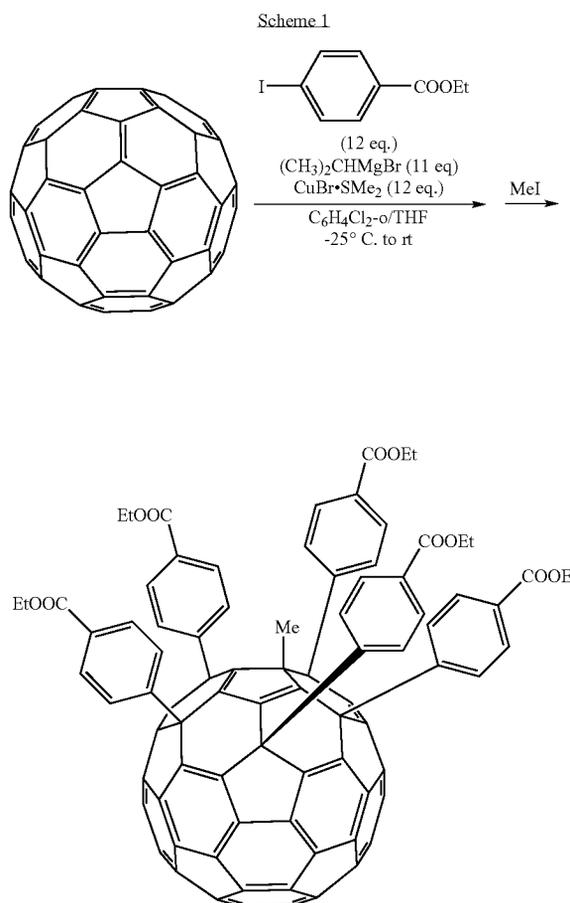
[0076] Hereinafter, the present invention will be more specifically described by way of examples. However, the present invention is not limited only to these examples.

##### Synthesis Example 1

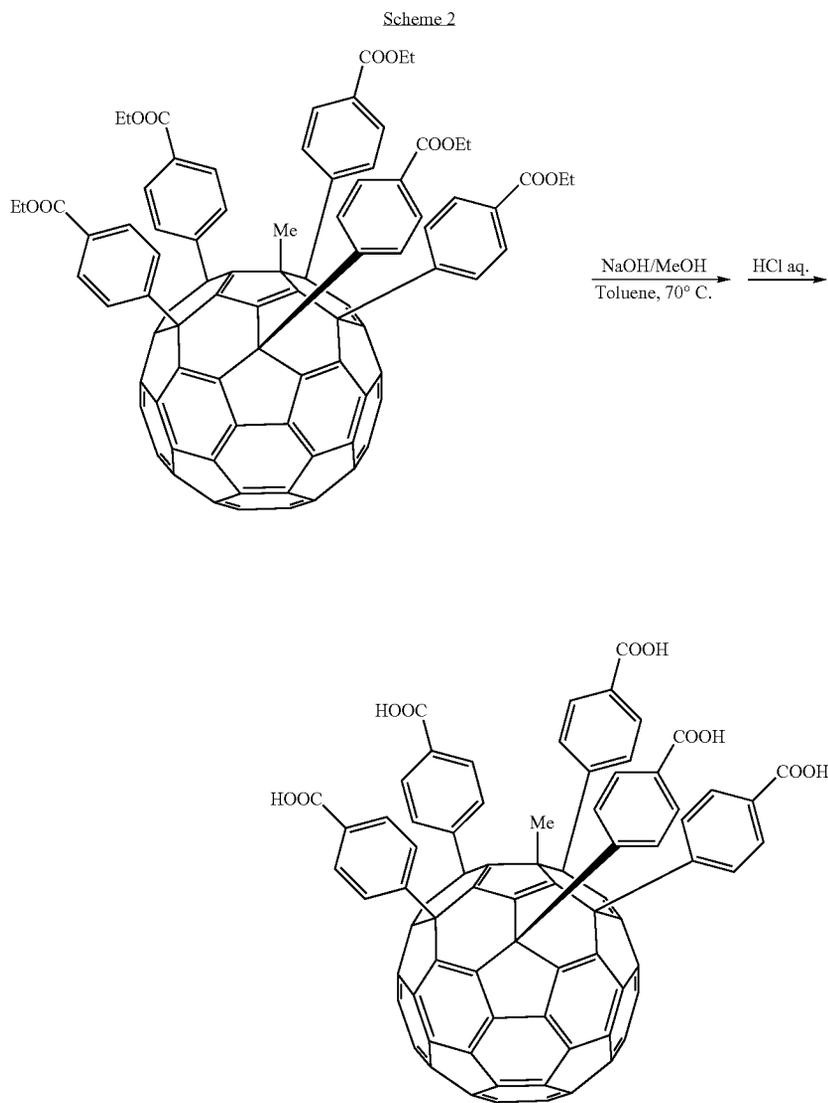
##### Production of $C_{60}(C_6H_4COOH-4)_5CH_3$

[0077] As shown in the below scheme 1, 72 mg of fullerene  $C_{60}$  was dissolved in 5 mL of orthodichlorobenzene under nitrogen atmosphere, and to the obtained mixture, 12 equivalents of 4-iodobenzoic acid ethyl ester, 11 equivalents of isopropyl Grignard reagent  $(CH_3)_2CHMgCl$  in THF solution (concentration: about 0.7 M), and 12 equivalents of copper (I) bromide-dimethylsulfide complex  $CuBr \cdot S(CH_3)_2$  were added, and the mixture was reacted at  $-25^\circ C$ . After that, the reaction mixture was heated to room temperature, and stirred

for 2 hours. Then methyl iodide was added thereto and the mixture was reacted at  $70^\circ C$ . for 2 hours. To the obtained solution, 10 mL of deaerated toluene was added for dilution, and the mixture was passed through a short-pass silica gel column using toluene as a developing solvent to remove by-products such as magnesium salt, etc. The solvent was distilled away, and 100 mL of methanol was added. A solid obtained by reprecipitation was subjected to filtration, and thereafter it was washed with methanol and hexane to obtain 100 mg of penta(organo)fullerene derivative  $C_{60}(C_6H_4COO(C_2H_5)-4)_5CH_3$  (isolated yield: 74%).



[0078] Next, as shown in the below scheme 2, the obtained  $C_6(C_6H_4COO(C_2H_5)-4)_5CH_3$  (14.8 mg, 0.01 mmol) was dissolved in toluene (5 mL), and to the mixture, sodium hydroxide in methanol solution (0.5 mol/L, 0.20 mL, 0.10 mmol) was added. The reaction mixture was heated to  $60^\circ C$ . and stirred for 30 minutes. After cooled, a solid precipitated was obtained by filtration, and it was washed with hexane. To the obtained solid of sodium salt, 2 mL of 1 mol/L HCl aqueous solution was added for protonation treatment. A solid was obtained by filtration, washed with water, and dried under reduced pressure at  $70^\circ C$ . for 6 hours to obtain 13.0 mg of penta(organo)fullerene derivative  $C_{60}(C_6H_4COOH-4)_5CH_3$  (solid, yield: 95%).



**[0079]** NMR, IR and APCI-MS analysis data of the obtained product are as follows:

**[0080]**  $^1\text{H NMR}$  (THF- $d_8$ ):  $\delta$  1.59 (s, 3H, Me), 7.36 (d,  $J=8.40$  Hz, 2H, ArH), 7.75 (d,  $J=8.40$  Hz, 2H, ArH), 7.95 (d,  $J=8.40$  Hz, 4H, ArH), 8.05 (m, 12H, ArH), 11.53 (s, br, 5H, COOH).  $^{13}\text{C NMR}$  (THF- $d_8$ ):  $\delta$  30.64 ( $\text{C}_{60}\text{CH}_3$ ), 59.18 (2C,  $\text{C}_{60}(\text{C}_\alpha)$ ), 62.12 (2C,  $\text{C}_{60}(\text{C}_\alpha)$ ), 63.48 (1C,  $\text{C}_{60}(\text{C}_\alpha)$ ), 63.50 ( $\text{C}_{60}(\text{C})\text{Me}$ ), 129.00, 129.45, 130.45, 130.68, 130.92, 131.13, 131.40, 131.81, 131.99, 143.10, 143.47, 143.72, 144.53, 144.66, 144.73, 144.98, 145.18, 145.22, 145.32, 145.56, 146.34, 146.68, 147.57, 148.04, 148.24, 148.58, 148.78, 149.08, 149.14, 149.26, 149.38, 149.56, 149.70, 152.60, 153.61, 157.79, 161.63, 166.80 (1C, COOH), 167.01 (2C, COOH), 167.05 (2C, COOH).

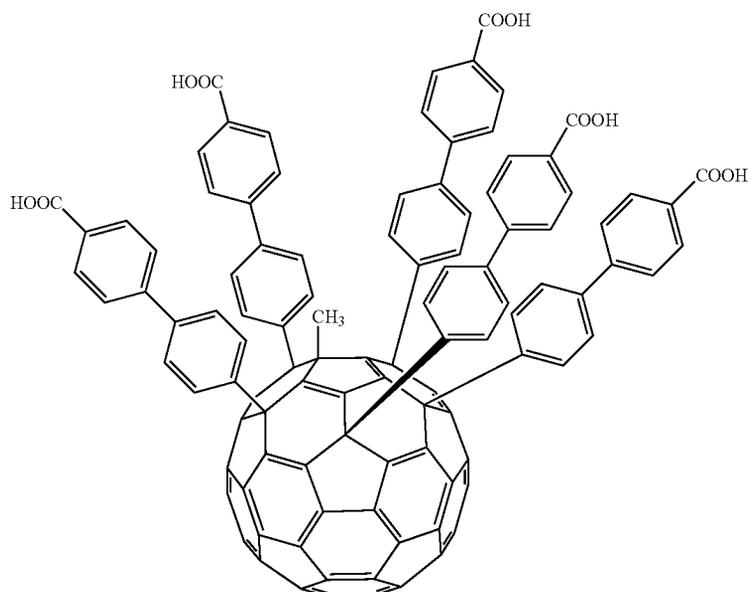
**[0081]** IR (powder,  $\text{cm}^{-1}$ ): 3390-2910 (br,  $\nu_{\text{O-H}}$ ), 1694 (m,  $\nu_{\text{C=O}}$ ), 1607 (s), 1270 ( $\nu_{\text{C-O}}$ ), 1102 (s), 1019 (s), 752 (s).

**[0082]** APCI-MS (-):  $m/z$  1340 ( $\text{M}^-$ ). APCI-HRMS (-): calcd for  $\text{C}_{96}\text{H}_{28}\text{O}_{10}$  ( $\text{M}^-$ ) 1340.1682, found 1340.1661.

#### Synthesis Example 2

##### Production of $\text{C}_{60}(\text{C}_6\text{H}_4\text{C}_6\text{H}_4\text{COOH-4})_5\text{CH}_3$

**[0083]** The produced  $\text{C}_{60}(\text{C}_6\text{H}_4\text{C}_6\text{H}_4\text{COO}(\text{C}_2\text{H}_5)\text{-4})_5\text{CH}_3$  (24.4 mg, 0.0132 mmol) was dissolved in toluene (5 mL), and to the obtained mixture, sodium hydroxide in methanol solution (0.5 mol/L, 0.15 mL, 0.15 mmol) was added. The reaction mixture was heated to  $60^\circ \text{C}$ . and stirred for 2 hours. After cooled, a solid precipitated was obtained by filtration, and washed with hexane. To the obtained solid of sodium salt, 1 mL of 1 mol/L HCl aqueous solution was added for protonation treatment. A solid was obtained by filtration, washed with water, and dried under reduced pressure at  $70^\circ \text{C}$ . for 6 hours to obtain 20.0 mg of penta(organo)fullerene derivative  $\text{C}_{60}(\text{C}_6\text{H}_4\text{C}_6\text{H}_4\text{COOH-4})_5\text{CH}_3$  (solid, yield: 88%).



**[0084]** NMR and APCI-MS analysis data of the obtained product are as follows:

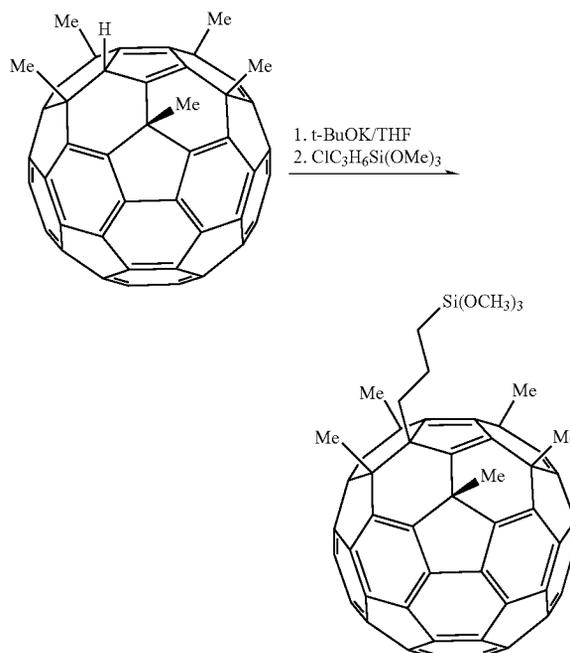
**[0085]**  $^1\text{H}$  NMR (500 MHz, THF-d8):  $\delta$  1.53 (s, 3H, Me), 7.46 (d,  $J=8.00$  Hz, 2H, ArH), 7.51 (d,  $J=8.00$  Hz, 2H, ArH), 7.61 (d,  $J=8.55$  Hz, 2H, ArH), 7.76-8.10 (m, 12H, ArH), 11.50 (s, br, 5H, COOH).  $^{13}\text{C}$  NMR (125 MHz, THF-d8):  $\delta$  32.59 ( $\text{C}_{60}\text{CH}_3$ ), 59.20 (2C,  $\text{C}_{60}(\text{C}_\alpha)$ ), 62.10 (2C,  $\text{C}_{60}(\text{C}_\alpha)$ ), 63.50 (1C,  $\text{C}_{60}(\text{C}_\alpha)$ ), 127.46, 127.69, 127.73, 127.88, 128.51, 128.77, 129.80, 130.41, 130.75, 130.82, 130.96, 131.06, 131.10, 131.18, 140.34, 140.71, 140.83, 143.74, 144.50, 144.91, 145.01, 145.11, 145.26, 145.36, 145.86, 146.50, 146.87, 148.29, 148.80, 149.19, 149.32, 149.44, 149.55, 149.71, 153.38, 154.17, 157.92, 158.37, 161.55, 167.36 (1C, COOH), 167.41 (2C, COOH), 167.43 (2C, COOH). APCI-HRMS (-): calcd for  $\text{C}_{126}\text{H}_{48}\text{O}_{10}$  [ $\text{M}-\text{H}$ ] $^-$  1720.32029, found 1720.31655.

### Synthesis Example 3

#### Production of $\text{C}_{60}(\text{CH}_3)_5\text{C}_3\text{H}_6\text{Si}(\text{OCH}_3)_3$

**[0086]** As shown in the below scheme 3, 106 mg of  $\text{C}_{60}(\text{CH}_3)_5\text{H}$  was dissolved in 5 mL of THF under nitrogen atmosphere. To this mixture, 1 equivalent of t-BuOK in THF solution was added, and then 2 equivalents of 3-trimethoxysilylpropylchloride was added, and the obtained mixture was reacted at 45° C. for 24 hours. After that, the reaction mixture was cooled to room temperature, and 0.2 mL of aqueous solution of ammonium chloride was added thereto to quench the reaction. 300 mL of methanol was added to the mixture, and a solid obtained by reprecipitation was filtered. After that, the solid was washed with methanol to obtain 128 mg of  $\text{C}_{60}(\text{CH}_3)_5\text{C}_3\text{H}_6\text{Si}(\text{OCH}_3)_3$  (isolated yield: 88%).

Scheme 3



**[0087]** NMR and APCI-MS analysis data of the obtained product are as follows:

**[0088]**  $^1\text{H}$  NMR (500 MHz,  $\text{CDCl}_3$ ):  $\delta$  0.90 (t,  $J=8.0$  Hz, 2H,  $\text{SiCH}_2$ ), 2.00 (m, 2H,  $\text{SiCH}_2\text{CH}_2$ ), 2.21 (s, 6H,  $\text{C}_{60}\text{CH}_3$ ), 2.33 (s, 6H,  $\text{C}_{60}\text{CH}_3$ ), 2.40 (s, 3H,  $\text{C}_{60}\text{CH}_3$ ), 2.60 (t,  $J=8.0$  Hz, 2H,  $\text{C}_{60}\text{CH}_2$ ), 3.71 (s, 9H, OCH<sub>3</sub>). APCI-HRMS (-): calcd for  $\text{C}_{71}\text{H}_2\text{O}_3\text{Si}$  ( $\text{M}^-$ -H) 958.1964, found 958.2002.

## Example 1

## Photoelectric Conversion Device Comprising ITO Electrode

[0089] An ITO electrode, wherein ITO was deposited on the surface of a transparent glass slide to get  $10 \Omega/\text{sq}$ , was immersed in 0.1 mM THF solution of  $\text{C}_{60}(\text{C}_6\text{H}_4\text{COOH-4})_5\text{CH}_3$  obtained in Synthesis Example 1 at  $23^\circ \text{C}$ . for 72 hours to prepare a self-assembled monomolecular film on ITO, and thereby a photoelectric conversion device was obtained.

[0090] Cathode current of the fullerene portion of the photoelectric conversion device was measured using a cyclic voltammetry method, and the amount of the current was integrated. As a result, the amount of faradaic current (S) was  $9.7 \mu\text{Ccm}^{-2}$ . According to the below formula, the amount of adsorption per ITO unit area, i.e., the number of molecules immobilized on the electrode ( $\Gamma^-$ ) was  $0.1 \text{ nmolcm}^{-2}$ .

$$\Gamma^- = S/F$$

[0091] ( $F$ =Faraday constant:  $96500 \text{ Cmol}^{-1}$ )  
 $\Gamma^- = 9.7 \mu\text{Ccm}^{-2}/96500 \text{ Cmol}^{-1} = 0.1 \text{ nmolcm}^{-2}$

## Example 2

## Photoelectric Conversion Device Comprising the Fullerene Derivative Obtained in Synthesis Example 2

[0092] A self-assembled monomolecular film was prepared on ITO in a manner similar to that in Example 1 except that the fullerene derivative  $\text{C}_{60}(\text{C}_6\text{H}_4\text{C}_6\text{H}_4\text{COOH-4})_5\text{CH}_3$  obtained in Synthesis Example 2 was used, and a photoelectric conversion device was produced. Further, when the number of molecules immobilized on the electrode ( $\Gamma^-$ ) was measured in a manner similar to that in Example 1, it was  $0.08 \text{ nmolcm}^{-2}$ .

## Comparative Example 1

## Photoelectric Conversion Device Comprising the Fullerene Derivative Obtained in Synthesis Example 3

[0093] A self-assembled monomolecular film was prepared on ITO in a manner similar to that in Example 1 except that the fullerene derivative  $\text{C}_{60}(\text{CH}_3)_5\text{C}_3\text{H}_6\text{Si}(\text{OCH}_3)_3$  obtained in Synthesis Example 3 was used, and a photoelectric conversion device was produced. Further, when the number of molecules immobilized on the electrode ( $F$ ) was measured in a manner similar to that in Example 1, it was  $0.24 \text{ nmolcm}^{-2}$ .

## Example 3

## Solar Cell Comprising the Photoelectric Conversion Device in Example 1

[0094] The photoelectric conversion device laminated with the self-assembled monomolecular film of  $\text{C}_{60}(\text{C}_6\text{H COOH-4})_5\text{CH}_3$  obtained in Example 1 was used as a work electrode, and a platinum wire was used as a counter electrode. These two electrodes were positioned to be opposed in an electrolyte solution, wherein ascorbic acid (AsA, as an electron donor) was dissolved in an aqueous solution comprising 0.1 mol of sodium sulfate, and thereby the solar cell of the present invention was produced. In this case, the electrolyte solution exists between the two electrodes to function as a charge transfer layer.

[0095] Further, using an Ag/AgCl electrode as a reference electrode, under the condition of temperature at  $25^\circ \text{C}$ ., the aforementioned solar cell was subjected to photocurrent measurement.

[0096] When the electrical potential of the work electrode was set as 0 V and the solar cell was irradiated with monochromatic light from a Xe lamp (wavelength: 400 nm, intensity:  $407 \mu\text{W}$ ), anode current was observed. In this case, the absorbance (A) was  $2.34 \times 10^{-4}$ , and the photocurrent (i) was  $30.7 \times 10^{-9} \text{ A}$ .

[0097] According to the below formula, the quantum yield ( $\phi$ ), which represents the ratio between the number of photons absorbed by the compound on ITO and the number of electrons flowed, was 44%.

$$\text{Quantum yield } (\phi) = (i/e)/[I(1-10^{-4})] \times 100 (\%)$$

[0098] In this regard,  $I = (W\lambda/hc)$ , which means the number of photons per unit time and unit area ( $8.2 \times 10^{14} \text{ WJ}$ ); i represents a photocurrent (A); and A represents absorbance at  $\lambda$  nm. Further, e represents elementary charge ( $C$ )= $1.60 \times 10^{-19} \text{ C}$ ; W represents light irradiation power (W) at  $\lambda \text{ nm} = 407 \times 10^{-6} \text{ W}$  (used in the experiment);  $\lambda$  represents wavelength of light irradiation (m)=400 nm (used in the experiment); h represents Planck's constant (Js)= $6.63 \times 10^{-34} \text{ JS}$ ; and c represents light speed ( $\text{ms}^{-1}$ )= $3.00 \times 10^8 \text{ ms}^{-1}$ .

[0099] When the electrical potential of the work electrode was set as +0.1 V and bias voltage was provided, the photocurrent (i) was  $68.0 \times 10^{-9} \text{ A}$ . In this case, the quantum yield ( $\phi$ ) was 95%.

[0100] Further, the photocurrent spectrum obtained when irradiated with light having the wavelength of 400 to 600 nm showed almost the same shape as the absorption spectrum of  $\text{C}_{60}(\text{C}_6\text{H COOH-4})_5\text{CH}_3$  in THF solution. According to the result, it was confirmed that  $\text{C}_{60}(\text{C}_6\text{H COOH-4})_5\text{CH}_3$  is the active center of photoelectric conversion.

## Example 4

## Solar Cell Comprising the Photoelectric Conversion Device in Example 2

[0101] The solar cell of the present invention was produced in a manner similar to that in Example 3 except that the photoelectric conversion device in Example 2 was used.

[0102] When the electrical potential of the work electrode was set as 0 V and the solar cell was irradiated with monochromatic light from a Xe lamp (wavelength: 400 nm, intensity:  $407 \mu\text{W}$ ) in a manner similar to that in Example 3, anode current was observed. In this case, the absorbance (A) was  $1.87 \times 10^{-4}$ , and the photocurrent (i) was  $22.5 \times 10^{-9} \text{ A}$ . According to the above-described formula, the quantum yield ( $\phi$ ), which represents the ratio between the number of photons absorbed by the compound on ITO and the number of electrons flowed, was 40%.

[0103] When the electrical potential of the work electrode was set as 0.1 V and bias voltage was provided, the photocurrent (i) was  $45.0 \times 10^{-9} \text{ A}$ . In this case, the quantum yield ( $\phi$ ) was 80%.

[0104] Further, the photocurrent spectrum obtained when irradiated with light having the wavelength of 400 to 600 nm showed almost the same shape as the absorption spectrum of  $\text{C}_{60}(\text{C}_6\text{H}_4\text{C}_6\text{H COOH-4})_5\text{CH}_3$  in THF solution. According to the result, it was confirmed that  $\text{C}_{60}(\text{C}_6\text{H}_4\text{C}_6\text{H COOH-4})_5\text{CH}_3$  is the active center of photoelectric conversion.

## Comparative Example 2

## Solar Cell Comprising the Photoelectric Conversion Device in Comparative Example 1

[0105] The solar cell of the present invention was produced in a manner similar to that in Example 4 except that the photoelectric conversion device in Comparative Example 1 was used.

[0106] When the electrical potential of the work electrode was set as 0 V and the solar cell was irradiated with monochromatic light from a Xe lamp (wavelength: 400 nm, intensity: 407  $\mu\text{w}$ ) in a manner similar to that in Example 4, anode current was observed. In this case, the absorbance (A) was  $5.18 \times 10^{-4}$ , and the photocurrent (i) was  $4.4 \times 10^{-9}$  A. According to the above-described formula, the quantum yield ( $\phi$ ), which represents the ratio between the number of photons absorbed by the compound on ITO and the number of electrons flowed, was 2.8%.

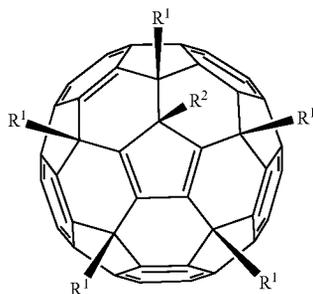
[0107] When the electrical potential of the work electrode was set as 0.07 V and bias voltage was provided, the photocurrent (i) was  $12.8 \times 10^{-9}$  A. In this case, the quantum yield ( $\phi$ ) was 8.2%.

[0108] Further, the photocurrent spectrum obtained when irradiated with light having the wavelength of 400 to 600 nm showed almost the same shape as the absorption spectrum of  $\text{C}_{60}(\text{CH}_3)_5\text{C}_3\text{H}_6\text{Si}(\text{OCH}_3)_3$  in THF solution. According to the result, it was confirmed that  $\text{C}_{60}(\text{CH}_3)_5\text{C}_3\text{H}_6\text{Si}(\text{OCH}_3)_3$  is the active center of photoelectric conversion.

#### INDUSTRIAL APPLICABILITY

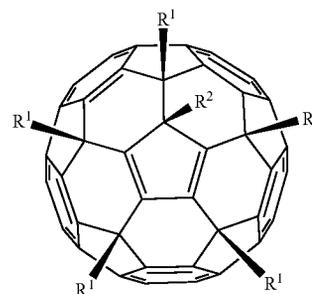
[0109] The photoelectric conversion material and the photoelectric conversion device obtained in the present invention can be utilized, for example, for organic solar cell, etc.

1. A photoelectric conversion material comprising a fullerene derivative represented by the following formula (1):



wherein: each  $\text{R}^1$  independently represents a hydrogen atom, a substituted or unsubstituted  $\text{C}_1$ - $\text{C}_{30}$  hydrocarbon group, a substituted or unsubstituted  $\text{C}_1$ - $\text{C}_{30}$  alkoxy group, a substituted or unsubstituted  $\text{C}_6$ - $\text{C}_{30}$  aryloxy group, a substituted or unsubstituted amino group, a substituted or unsubstituted silyl group, a substituted or unsubstituted alkylthio group ( $-\text{SY}^1$ : in the formula,  $\text{Y}^1$  represents a substituted or unsubstituted  $\text{C}_1$ - $\text{C}_{30}$  alkyl group), a substituted or unsubstituted arylthio group ( $-\text{SY}^2$ : in the formula,  $\text{Y}^2$  represents a substituted or unsubstituted  $\text{C}_6$ - $\text{C}_{18}$  aryl group), a substituted or unsubstituted alkylsulfonyl group ( $-\text{SO}_2\text{Y}^3$ : in the formula,  $\text{Y}^3$  represents a substituted or unsubstituted  $\text{C}_1$ - $\text{C}_{30}$  alkyl group), or a substituted or unsubstituted arylsulfonyl group ( $-\text{SO}_2\text{Y}^4$ : in the formula,  $\text{Y}^4$  represents a substituted or unsubstituted  $\text{C}_6$ - $\text{C}_{18}$  aryl group); and  $\text{R}^2$  represents a hydrogen atom or a substituted or unsubstituted  $\text{C}_1$ - $\text{C}_{30}$  hydrocarbon group.

2. A photoelectric conversion material comprising a fullerene derivative represented by the following formula (1):

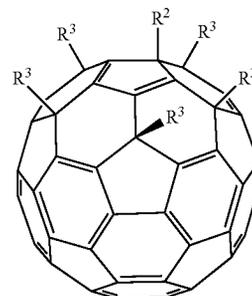


wherein: each  $\text{R}^1$  independently represents a  $\text{C}_1$ - $\text{C}_{30}$  hydrocarbon group, a  $\text{C}_1$ - $\text{C}_{30}$  alkoxy group, a  $\text{C}_6$ - $\text{C}_{30}$  aryloxy group, an amino group, a silyl group, an alkylthio group ( $-\text{SY}^1$ : in the formula,  $\text{Y}^1$  represents a substituted or unsubstituted  $\text{C}_1$ - $\text{C}_{30}$  alkyl group), an arylthio group ( $-\text{SY}^2$ : in the formula,  $\text{Y}^2$  represents a substituted or unsubstituted  $\text{C}_6$ - $\text{C}_{18}$  aryl group), an alkylsulfonyl group ( $-\text{SO}_2\text{Y}^3$ : in the formula,  $\text{Y}^3$  represents a substituted or unsubstituted  $\text{C}_1$ - $\text{C}_{30}$  alkyl group), or an arylsulfonyl group ( $-\text{SO}_2\text{Y}^4$ : in the formula,  $\text{Y}^4$  represents a substituted or unsubstituted  $\text{C}_6$ - $\text{C}_{18}$  aryl group), which has a carboxylic acid group, a phosphate group or a phosphonate group; and  $\text{R}^2$  represents a hydrogen atom or a substituted or unsubstituted  $\text{C}_1$ - $\text{C}_{30}$  hydrocarbon group.

(1)

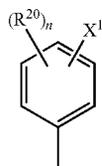
3. The photoelectric conversion material according to claim 2, wherein: each  $\text{R}^1$  independently represents a  $\text{C}_1$ - $\text{C}_{30}$  alkyl group, a  $\text{C}_2$ - $\text{C}_{30}$  alkenyl group, a  $\text{C}_2$ - $\text{C}_{30}$  alkynyl group, a  $\text{C}_4$ - $\text{C}_{30}$  alkyldienyl group, a  $\text{C}_6$ - $\text{C}_{18}$  aryl group, a  $\text{C}_7$ - $\text{C}_{30}$  alkylaryl group, a  $\text{C}_7$ - $\text{C}_{30}$  arylalkyl group, a  $\text{C}_4$ - $\text{C}_{30}$  cycloalkyl group or a  $\text{C}_4$ - $\text{C}_{30}$  cycloalkenyl group, which has a carboxylic acid group, a phosphate group or a phosphonate group; and  $\text{R}^2$  represents a hydrogen atom or a  $\text{C}_1$ - $\text{C}_{30}$  alkyl group.

4. A photoelectric conversion material comprising a fullerene derivative represented by the following formula (10):



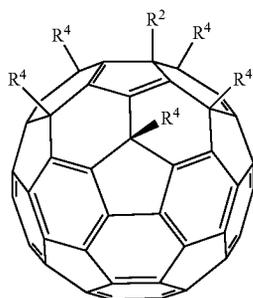
(10)

wherein:  $\text{R}^2$  represents a hydrogen atom or a substituted or unsubstituted  $\text{C}_1$ - $\text{C}_{30}$  hydrocarbon group; and each  $\text{R}^3$  is independently a group represented by the following formula (A):

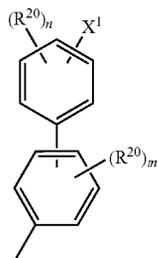


wherein:  $X^1$  represents a carboxylic acid group, a phosphate group or a phosphonate group; each  $R^{20}$  independently represents an organic group; and  $n$  is an integer from 0 to 4.

5. A photoelectric conversion material comprising a fullerene derivative represented by the following formula (11):



wherein:  $R^2$  represents a hydrogen atom or a substituted or unsubstituted  $C_1$ - $C_{30}$  hydrocarbon group; each  $R^4$  is independently a group represented by the following formula (B):



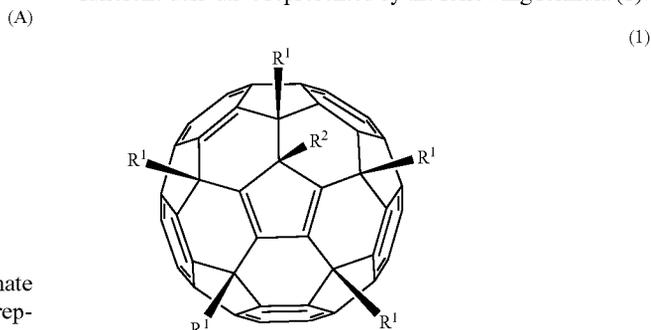
wherein:  $X^1$  represents a carboxylic acid group, a phosphate group or a phosphonate group;  $M$  represents a metal atom; each  $R^{20}$  independently represents an organic group;  $n$  is an integer from 0 to 4; and  $m$  is an integer from 0 to 4.

6. A photoelectric conversion device having a self-assembled monomolecular film of the photoelectric conversion material according to claim 2.

7. A photoelectric conversion device having an ITO electrode on which the self-assembled monomolecular film of the photoelectric conversion material according to claim 2 is formed.

8. A solar cell having the photoelectric conversion device according to claim 6.

9. A photoelectric conversion material comprising a fullerene derivative represented by the following formula (1):



wherein: each  $R^1$  independently represents a  $C_1$ - $C_{30}$  hydrocarbon group, a  $C_1$ - $C_{30}$  alkoxy group, a  $C_6$ - $C_{30}$  aryloxy group, an amino group, a silyl group, an alkylthio group ( $-SY^1$ : in the formula,  $Y^2$  represents a substituted or unsubstituted  $C_1$ - $C_{30}$  alkyl group), an arylthio group ( $-SY^2$ : in the formula,  $Y^2$  represents a substituted or unsubstituted  $C_6$ - $C_{18}$  aryl group), an alkylsulfonyl group ( $-SO_2Y^3$ : in the formula,  $Y^3$  represents a substituted or unsubstituted  $C_1$ - $C_{30}$  alkyl group), or an arylsulfonyl group ( $-SO_2Y^4$ : in the formula,  $Y^4$  represents a substituted or unsubstituted  $C_6$ - $C_8$  aryl group), which has a thiol group or a disulfide group; and  $R^2$  represents a hydrogen atom or a substituted or unsubstituted  $C_1$ - $C_{30}$  hydrocarbon group.

10. The photoelectric conversion material according to claim 9, wherein: each  $R^1$  independently represents a  $C_1$ - $C_{30}$  alkyl group, a  $C_2$ - $C_{30}$  alkenyl group, a  $C_2$ - $C_{30}$  alkynyl group, a  $C_4$ - $C_{30}$  alkyldienyl group, a  $C_6$ - $C_{18}$  aryl group, a  $C_7$ - $C_{30}$  alkylaryl group, a  $C_7$ - $C_{30}$  arylalkyl group, a  $C_4$ - $C_{30}$  cycloalkyl group or a  $C_4$ - $C_{30}$  cycloalkenyl group, which has a thiol group or a disulfide group; and  $R^2$  represents a hydrogen atom or a  $C_1$ - $C_{30}$  alkyl group.

11. A photoelectric conversion device having a self-assembled monomolecular film of the photoelectric conversion material according to claim 9.

12. A photoelectric conversion device having a gold electrode on which the self-assembled monomolecular film of the photoelectric conversion material according to claim 9 is formed.

13. A solar cell having the photoelectric conversion device according to claim 11.

14. A photoelectric conversion device having a self-assembled monomolecular film of the photoelectric conversion material according to claim 3.

15. A photoelectric conversion device having a self-assembled monomolecular film of the photoelectric conversion material according to claim 4.

16. A photoelectric conversion device having a self-assembled monomolecular film of the photoelectric conversion material according to claim 5.

17. A solar cell having the photoelectric conversion device according to claim 7.

18. A photoelectric conversion device having a self-assembled monomolecular film of the photoelectric conversion material according to claim 10.

19. A photoelectric conversion device having a gold electrode on which the self-assembled monomolecular film of the photoelectric conversion material according to claim 10 is formed.

20. A solar cell having the photoelectric conversion device according to claim 12.

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