

Description

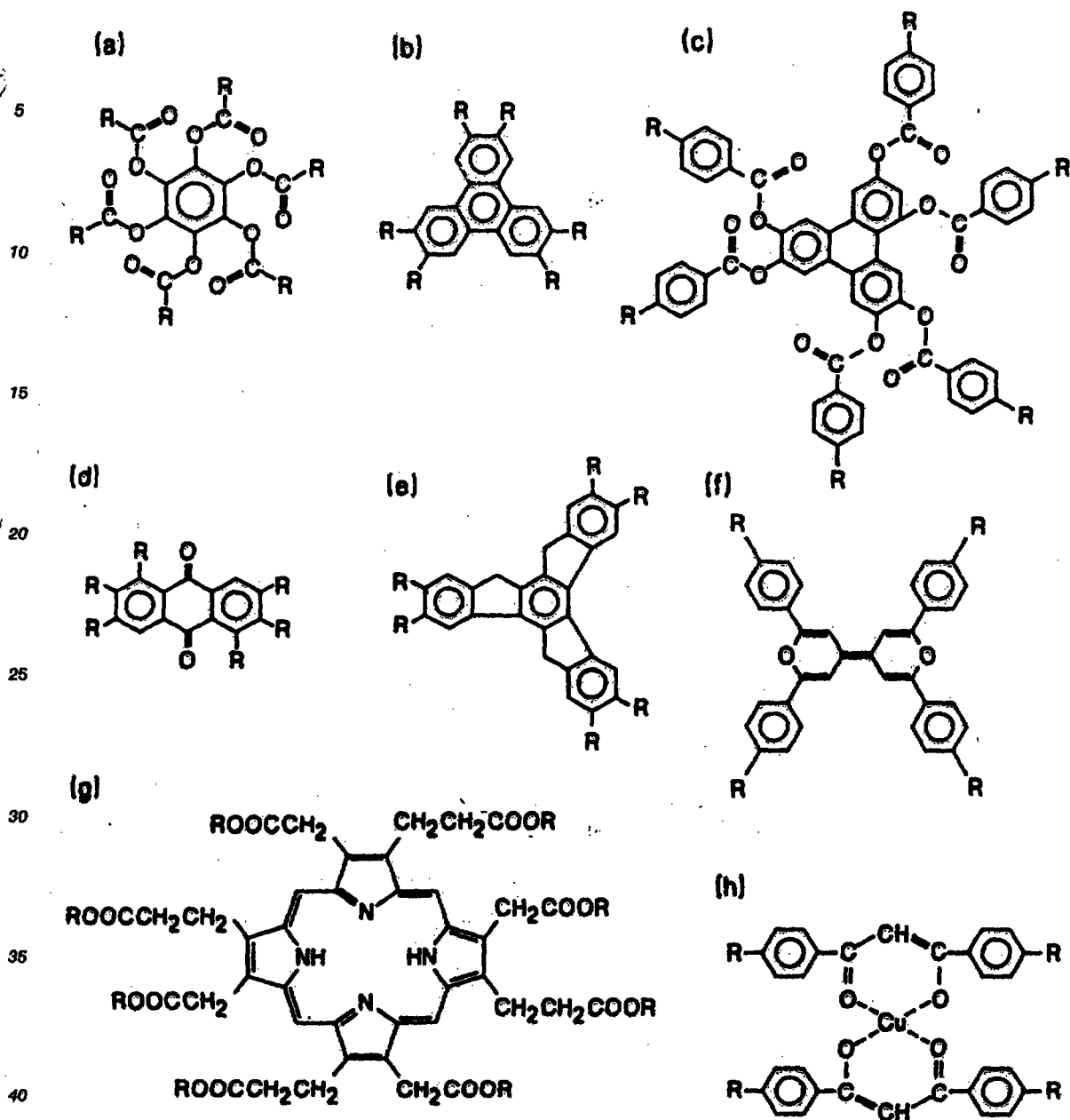
This invention relates to novel materials which are semi-conducting liquid crystals, and to electronic devices incorporating these novel materials.

Conventional thermotropic liquid crystals are electrical insulators. Electronically conducting liquid crystals have been recognised as potentially valuable entities combining the properties of a semi-conductor with those of a liquid crystal. Attempts to prepare such a material have met with limited success. Mesogens containing a metal atom exhibit very low isotropic conductivity and charge transfer complexes of mesogen molecules exhibit lower conductivity in the liquid crystalline phase than in the solid phase. DE-A- 3 625 154 discloses a process for producing a semi-conductive liquid crystalline material, which is a radical salt of a mesogen, comprising heating a mixture of a dopant and a mesogen at elevated temperature Drenth et al - (Recl. Trav. Chim. Pays-Bas, 106, (1987) 534) reported that doping a hexa alkoxytriphenylene mesogen with 0.7 moles of iodine per mole of mesogen increases the conductivity but that the doped product exhibits isotropic ionic conduction properties.

We have now discovered that semi-conducting liquid crystals capable of exhibiting anisotropic electronic conduction properties can be produced by introducing a quantity of dopant which can be much smaller than utilised by Drenth so as to form a material which comprises a radical salt of the mesogen. Accordingly from one aspect our invention provides a semi-conducting liquid crystal which comprises a radical salt of a mesogen.

The mesogens from which the novel liquid crystals of this invention may be produced are those thermotropic mesogens which are capable of forming a radical salt, i.e. either a radical anion or a radical cation. Preferably the radical salts are stable. The mesogens capable of forming such salts preferably comprise aromatic moieties as part of their molecular structure since the charge on the radical can then be delocalised over the aromatic ring or rings. The mesogens may be those which form a columnar mesophase a smectic phase, or may be those which form a nematic mesophase.

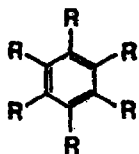
A preferred class of mesogens are the disc-like (discotic) mesogens, e.g. those reported by S. Chandrasekhar in Phil. Trans. R. Soc. London, A 309, 93-103 (1983), which have the following formulae:-



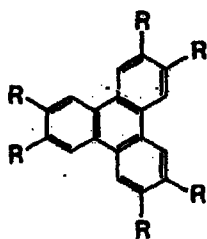
wherein (a) are the hexa-n-alkanoates of benzene; (b) are the hexa-n-alkanoates of triphenylene and hexa-n-alkoxytriphenylene; (c) are the hexa-n-alkyl and alkoxybenzoates of triphenylene; (d) ruffigallol-hexanoate; (e) are the hexa-n-alkanoates of truxene the (hex-a-n-alkanoates of oxatruxene are also useful); (f) are the 2,2',6,6'-tetra-arylbi-4-pyran-4-ylidenes; (g) is uroporphyrin I octa-n-dodecyl ester and (h) is bis(p-n-decylbenzoyl)methanato copper (II).

Examples of other discotic mesogens which have been reported in the literature include:-

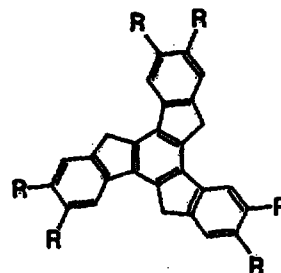
ARENE CORES



1. $R = \text{OCOC}_7\text{H}_{15}$

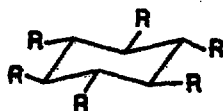


2. $R = \text{OCOC}_6\text{H}_4\text{OC}_8\text{H}_{17}$
 $R = \text{SC}_6\text{H}_{13}$

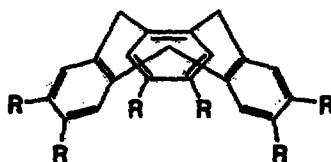


3. $R = \text{OCOC}_{13}\text{H}_{26}$

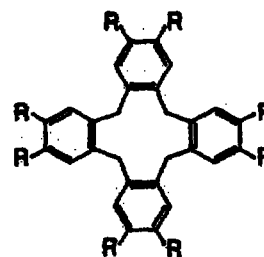
ALICYCLIC CORES



4. $R = \text{OCOC}_7\text{H}_{15}$

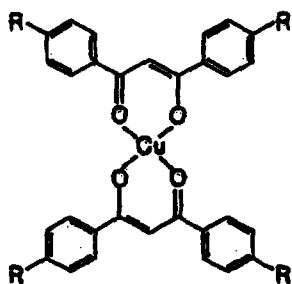


5. $R = \text{OCOC}_{10}\text{H}_{21}$

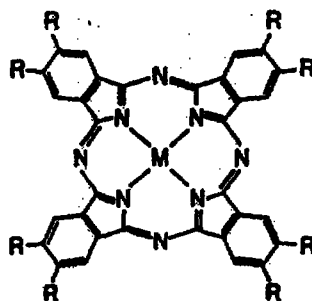


6. $R = \text{OCOC}_{11}\text{H}_{23}$

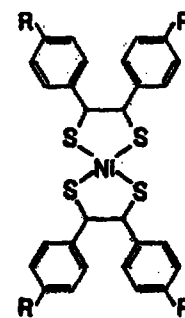
ORGANOMETALLIC CORES



7. $R = \text{C}_8\text{H}_{17}$

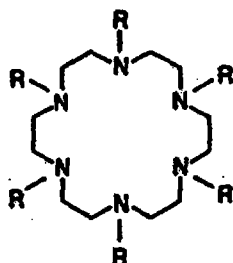


8. $R = \text{CH}_2\text{OC}_{12}\text{H}_{25}$
 $M = 2\text{H}$
 $M = \text{Cu}$



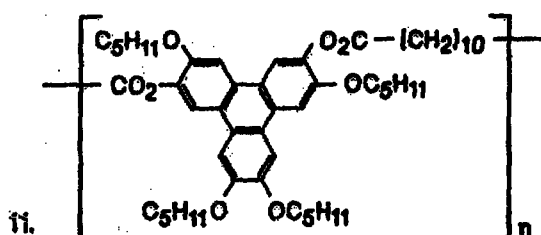
9. $R = \text{OC}_9\text{H}_{19}$

HETEROCYCLIC CORES



10. $R = \text{COC}_6\text{H}_4\text{OC}_{12}\text{H}_{25}$

POLYMERS

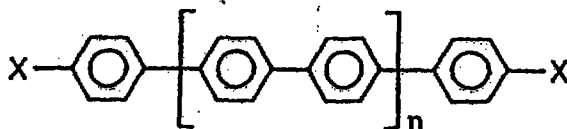


11.

Homologues and analogues of any of these compounds which exhibit a discotic liquid crystal phase are potentially useful according to this invention.

These disc-like mesogens form either columnar or nematic mesophases. The radical salts of such mesogens conduct in only one or in one strongly preferred dimension when appropriately oriented and such oriented materials represent a preferred aspect of the invention.

A further class of mesogens which can form radical salts and from which semi-conducting liquid crystals capable of exhibiting anisotropic electronic conduction properties may be produced are rod-like molecules having a polyaromatic unit as part of their molecular structure such as a polybenzene unit having the following formula:-



wherein X represents any suitable end chain such as an alkyl or alkoxy group and n is an integer having a value of at least 1. Also, rod-like mesogens in which at least two of the aromatic rings are linked through suitable groups such as $-\text{N}=\text{N}-$; $-\text{N}=\text{N}\text{O}-$; $-\text{CH}=\text{CH}-\text{C}\equiv\text{C}-$; or $-\text{CO}_2-\text{CH}=\text{N}-$ groups. These rod like mesogens form either smectic or nematic phases.

A further group of compounds which can form radical salts are liquid crystal polymers in which any of the above mesogenic units are incorporated either in the main chain backbone or attached in one or more pendant side chains.

The radical salts of such mesogens conduct in only one or two clearly preferred dimensions when appropriately oriented and such oriented materials represent a further preferred aspect of our invention.

The radical salts of the mesogens are formed by doping the mesogen with an oxidising or a reducing agent. The nature of the dopant and the quantity in which it is employed should be selected so as not to alter either the structure or the stability of the mesophase to any significant degree. The dopant is utilised in a quantity which is not more than 0.5 moles per mole of mesogen and is preferably not more than 0.25 and most preferably not more than 0.1 moles per mole of mesogen. In general the conductivity of the mesogen will be proportional to the quantity of dopant which is utilised. It will be appreciated that where the charge is delocalised the material does not exist as a mixture of the mesogen and its radical salt but rather as a mesogen having a net excess or deficiency of electrons. Nevertheless for convenience this description refers to the formation of a radical salt in these circumstances.

A wide variety of dopants may be utilised. Examples of dopants which may be useful include electron acceptors such as iodine, aluminium trichloride, aluminium tribromide and antimony pentafluoride and electron donors such as dimethyl sulphide and lithium metal.

The dopant used to form the radical salt of the particular mesogen is preferably one which is miscible with the mesogen; at least in the quantity which is to be employed. The particular quantity which is preferably added varies with the nature of the mesogen for each particular dopant.

The formation of the radical salt is preferably carried out by heating a mixture of the dopant and the mesogen at a temperature at which they form an isotropic phase in the absence of oxygen. The temperature will usually be above or very close to the temperature at which the mesogen forms an isotropic phase since the presence of the dopant depresses this transition temperature to some extent. Such processes are believed to be novel and constitute a further aspect of this invention.

The formation of a radical salt of the mesogen may be confirmed by esr spectroscopy. The crystalline, liquid crystal and isotropic phases each exhibit characteristic esr spectra. The fact that these phases are formed is indicative of a dopant which has not disturbed the general phase behaviour of the mesogen.

The conductance of the doped mesogen is at least three and preferably at least five orders of magnitude greater than that of the undoped mesogen.

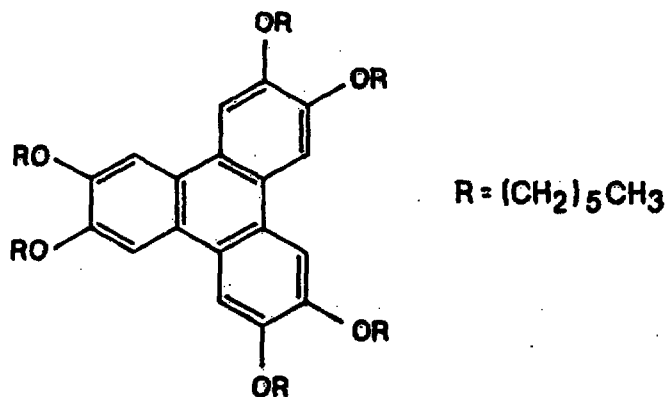
The anisotropic conductivity properties are exhibited when the doped mesogen is oriented in the mesophase. The degree of anisotropy of the conducting properties is proportional to the degree of orientation of the molecules in the mesophase. The preferred liquid crystals of this invention have a conductance in one or two dimensions which is at least 1.1 times and preferably 10 times greater than its conduction in at least one other dimension.

This anisotropy of conductance may be preserved when the doped oriented material is cooled into the crystalline phase. Crystalline phases of the mesogens of this invention which exhibit anisotropic conductivity form a preferred aspect of this invention.

The conduction properties of the novel liquid crystalline materials of this invention and the ease with which they can be fabricated as thin films render them useful in a variety of electronic, thermo-electronic and opto-electronic devices. The changes in the order of the materials which can be achieved by heating directly or with a laser or by the application of localized magnetic or electrical fields can be detected by changes in the conductivity and hence the materials may be useful in temperature sensors and information storage devices. The unique optical properties of the materials renders them useful in non-linear optics and other electro-optic applications. Electronic devices and electro-optic devices incorporating the novel materials form another aspect of our invention.

The invention is illustrated by the following example:-

The discotic mesogen 2,3,6,7,10,11-hexa-hexyloxytriphenylene (HAT6)



HAT6

was synthesized by chloranil oxidative trimerisation of veratrole, demethylation with hydrogen bromide, and alkylation of the hexaphenol produced. Doping was carried out under a vacuum by heating a mixture of HAT6 and $AlCl_3$ to 373 K. Transition temperatures were measured using a Perkin-Elmer DSC2 using indium as a calibration standard. The thermogram (Figure 1) of undoped HAT6 shows two endothermic peaks, corresponding to the crystal to columnar phase transition at 343 K, and the columnar to isotropic phase transition at 373 K. On doping with 1 mole per cent of $AlCl_3$ the transition temperatures are depressed (340 K and 370 K) and the endotherms are broadened.

A.C. electrical conductivity measurements were made using a Hewlett Packard model 4192a Impedance Analyser and a sample cell with 5 x 5 mm platinum electrodes coated with platinum black, and with separation 5 mm. The conductivity of HAT6 changes by at least six orders of magnitude when doped with $AlCl_3$ from less than $10^{-10} \text{ S m}^{-1}$ to approximately 10^{-4} - 10^{-3} S m^{-1} . In all three phases, the conductivity was found to be constant between 5 Hz and 25 kHz and then to increase approximately linearly with increasing frequency. The variation of the conductivity with temperature is shown in Figure 2.

Esr measurements were made on a sample contained under vacuum in a quartz tube of internal diameter 3 mm and filled to a depth of 15 mm using a Bruker ER 200 X-Band esr spectrometer. A modulation amplitude of $1.25 \times 10^{-5} \text{ T}$ was used for all measurements. For undoped HAT6, the esr signal is a single line of negligible intensity in all of the three phases, whilst for doped HAT6 the intensity of the line increases by at least five to six orders of magnitude. The intensity of the signal remained constant over the whole of the measured temperature range (293-403 K). In the crystalline phase, the signal has a Lorentzian shape, and there is a small yet steady decrease in the linewidth with increase in temperature (Figure 3a). At the crystal to columnar phase transition there are two distinct changes in the esr signal: (1) the linewidth decreases sharply by a factor of approximately 1.5; (2) the linewidth becomes asymmetric, the asymmetry increasing with increasing temperature (Figure 3b).

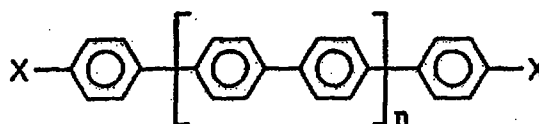
Orienting the columnar phase by cooling from the isotropic phase in the presence of a magnetic field (field strength 1.6T) produced a significant degree of anisotropy (approximately 10^{-2} S m^{-1}). This anisotropy of conductivity was preserved on cooling into the crystalline phase. The variation of conductivity with temperature is shown in Figure 4. $\sigma^\perp$ is the conductivity measured perpendicular to the magnetic field and $\sigma^\parallel$ is that measured parallel to the magnetic field. σ^0 is the electrical conductivity of the unaligned sample.

Doping of the HAT6 mesogen with aluminium tribromide, iodine and antimony pentafluoride also produced a radical salt of the mesogen which when suitably aligned exhibited anisotropic conduction properties.

Similarly doping of the mesogens 2, 3, 6, 7, 10, 11-hexahexylthiotriphenylene (HTT6) and 2, 3, 6, 7, 10, 11-hexa (paraundecyloxybenzoyloxy)triphenylene (HBT11) with aluminium trichloride, aluminium tribromide, iodine or antimony pentafluoride resulted in the production of a radical salt of the mesogen.

Claims

1. A semi-conducting liquid crystalline material which comprises a radical salt of a mesogen formed by doping the mesogen with not more than 0.5 moles of dopant per mole of mesogen, the dopant being an oxidising or a reducing agent.
2. A material according to Claim 1 characterised in that the mesogen molecule comprises an aromatic moiety.
3. A material according to either of Claims 1 or 2 characterised in that the mesogen is a disc-like mesogen.
4. A material according to any of the preceding claims characterized in that the mesogen is a hexa-n-alkanoate of triphenylene or a hexa-n-alkoxy- triphenylene.
5. A material according to Claim 4 characterised in that the mesogen is 2,3,6,7,10,11 hexa-hexyloxy triphenylene.
6. A material according to Claim 4 characterised in that the mesogen is 2, 3, 6, 7, 10, 11-hexa-hexylthiotriphenylene.
7. A material according to Claim 4 characterised in that the mesogen is 2, 3, 6, 7, 10, 11-hexa-(paraundecyloxybenzoyloxy) triphenylene.
8. A material according to Claim 2 characterized in that the mesogen molecule comprises a polyaromatic moiety having the formula:



wherein X represents an end-chain group and n is an integer having a value of at least 1.

9. A material according to Claim 8 characterized in that X represents an alkyl group or an alkoxy group.
10. A material according to Claim 2 characterized in that the mesogen molecule comprises at least two aromatic rings linked so as to form a rod-like molecule.
11. A material according to any of Claims 1 to 9 characterized in that the material is a liquid crystal polymer in which a radical salt of a mesogen is incorporated either in the main chain or in one or more pendant side chains.
12. A material according to any of the preceding claims characterised in that the mesogen comprises a radical cation.
13. A material according to any preceding claim characterised in that the dopant is selected from the group comprising aluminium trichloride, aluminium tribromide, iodine and antimony pentafluoride.

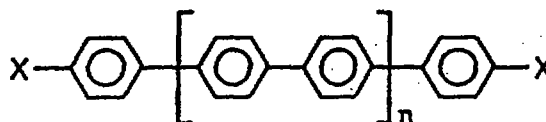


Doping of the HAT6 mesogen with aluminium tribromide, iodine and antimony pentafluoride also produced a radical salt of the mesogen which when suitably aligned exhibited anisotropic conduction properties.

Similarly doping of the mesogens 2, 3, 6, 7, 10, 11-hexahexylthiotriphenylene (HTT6) and 2, 3, 6, 7, 10, 11-hexa (paraundecyloxybenzoyloxy)triphenylene (HBT11) with aluminium trichloride, aluminium tribromide, iodine or antimony pentafluoride resulted in the production of a radical salt of the mesogen.

Claims

1. A semi-conducting liquid crystalline material which comprises a radical salt of a mesogen formed by doping the mesogen with not more than 0.5 moles of dopant per mole of mesogen, the dopant being an oxidising or a reducing agent.
2. A material according to Claim 1 characterised in that the mesogen molecule comprises an aromatic moiety.
3. A material according to either of Claims 1 or 2 characterised in that the mesogen is a disc-like mesogen.
4. A material according to any of the preceding claims characterized in that the mesogen is a hexa-n-alkanoate of triphenylene or a hexa-n-alkoxy- triphenylene.
5. A material according to Claim 4 characterised in that the mesogen is 2,3,6,7,10,11 hexa-hexyloxy triphenylene.
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7. A material according to Claim 4 characterised in that the mesogen is 2, 3, 6, 7, 10, 11-hexa-(paraundecyloxybenzoyloxy) triphenylene.
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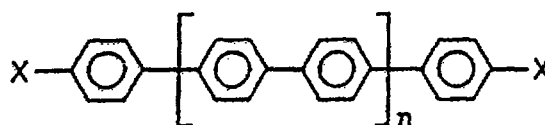
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10. A material according to Claim 2 characterized in that the mesogen molecule comprises at least two aromatic rings linked so as to form a rod-like molecule.
11. A material according to any of Claims 1 to 9 characterized in that the material is a liquid crystal polymer in which a radical salt of a mesogen is incorporated either in the main chain or in one or more pendant side chains.
12. A material according to any of the preceding claims characterised in that the mesogen comprises a radical cation.
13. A material according to any preceding claim characterised in that the dopant is selected from the group comprising aluminium trichloride, aluminium tribromide, iodine and antimony pentafluoride.



14. A material according to any preceding claim which comprises not more than 0.25 moles of dopant per mole of mesogen.
15. A material according to Claim 14, which comprises not more than 0.1 moles of dopant per mole of mesogen.
16. A material according to any of the preceding claims wherein the conductance of the liquid crystalline material in at least one dimension is 1.1 times greater than its conductance in one other dimension.
17. A material according to Claim 16 characterised in that the conductance of the liquid crystalline material in at least one dimension is at least 10 times greater than its conduction in one other dimension.
18. A material according to either of Claims 16 or 17 characterised in that the material is in its crystalline phase.
19. A process for the production of a semi-conducting liquid crystalline material which comprises mixing a mesogen which is capable of forming a radical salt with up to 0.5 times as many moles of a dopant which is an oxidising agent or a reducing agent.
20. A process according to Claim 19 characterised in that the mixture is heated to a temperature at which an isotropic phase is formed.
21. An electronic device incorporating at least one material as claimed in any of Claims 1 to 18 or which has been produced by a process according to Claim 19 or 20.

Patentansprüche

1. Halbleitendes, flüssigkristallines Material mit einem radikalischen Salz eines Mesogens, welches durch Dotierung des Mesogens mit nicht mehr als 0,5 Mol Dotierungsmittel pro Mol Mesogen gebildet wird, wobei das Dotierungsmittel ein oxidierendes oder reduzierendes Agens ist.
2. Material gemäß Anspruch 1, dadurch gekennzeichnet, daß das Mesogenmolekül einen aromatischen Rest besitzt.
3. Material gemäß Anspruch 1 oder 2, dadurch gekennzeichnet, daß das Mesogen ein Scheiben-ähnliches Mesogen ist.
4. Material gemäß irgendeinem der vorangegangenen Ansprüche, dadurch gekennzeichnet, daß das Mesogen ein Hexa-n-alkanoat von Triphenylen oder ein Hexa-n-alkoxytriphenylen ist.
5. Material gemäß Anspruch 4, dadurch gekennzeichnet, daß das Mesogen 2,3,6,7,10,11-Hexahexyloxytriphenylen ist.
6. Material gemäß Anspruch 4, dadurch gekennzeichnet, daß das Mesogen 2,3,6,7,10,11-Hexahexylthiotriphenylen ist.
7. Material gemäß Anspruch 4, dadurch gekennzeichnet, daß das Mesogen 2,3,6,7,10,11-Hexa(p-undecyloxybenzoyloxy)triphenylen ist.
8. Material gemäß Anspruch 2, dadurch gekennzeichnet, daß das Mesogenmolekül einen polyaromatischen Rest besitzt mit der Formel:



worin X eine Endgruppe darstellt und n eine ganze Zahl ist mit einem Wert von wenigstens 1.

- 10 9. Material gemäß Anspruch 8,
dadurch gekennzeichnet,
daß X eine Alkyl- oder eine Alkoxy-Gruppe darstellt.
- 15 10. Material gemäß Anspruch 2,
dadurch gekennzeichnet,
daß das Mesogenmolekül zumindest zwei aromatische Ringe so angefügt umfaßt, daß ein stäbchenförmiges Molekül gebildet wird.
- 20 11. Material gemäß irgendeinem der Ansprüche 1 bis 9,
dadurch gekennzeichnet,
daß das Material ein flüssigkristallines Polymer ist, in welchem ein radikalisches Salz eines Mesogens entweder in der Hauptkette oder in einer oder mehreren anhängenden Seitenketten integriert ist.
- 25 12. Material gemäß irgendeinem der vorangegangenen Ansprüche,
dadurch gekennzeichnet,
daß das Mesogen ein radikalisches Kation enthält.
- 30 13. Material gemäß irgendeinem der vorangegangenen Ansprüche,
dadurch gekennzeichnet,
daß das Dotierungsmittel ausgewählt ist aus der Gruppe mit Aluminiumtrichlorid, Aluminiumtribromid, Iod und Antimonpentafluorid.
- 35 14. Material gemäß irgendeinem der vorangegangenen Ansprüche,
welches nicht mehr als 0,25 Mol Dotierungsmittel pro Mol Mesogen enthält.
- 40 15. Material gemäß Anspruch 14,
welches nicht mehr als 0,1 Mol Dotierungsmittel pro Mol Mesogen enthält.
- 45 16. Material gemäß irgendeinem der vorangegangenen Ansprüche,
worin die Leitfähigkeit des flüssigkristallinen Materials in zumindest einer Dimension 1,1 mal größer ist als seine Leitfähigkeit in einer anderen Dimension.
- 50 17. Material gemäß Anspruch 16,
dadurch gekennzeichnet,
daß die Leitfähigkeit des flüssigkristallinen Materials in zumindest einer Dimension zumindest 10 mal größer ist als seine Leitfähigkeit in einer anderen Dimension.
- 55 18. Material gemäß Anspruch 16 oder 17,
dadurch gekennzeichnet,
daß das Material in seiner kristallinen Phase ist.
19. Verfahren zur Herstellung eines halbleitenden, flüssigkristallinen Materials, welches eine Mischung eines Mesogens, welches ein radikalisches Salz bilden kann, mit bis zu 0,5 mal so vielen Molen eines Dotierungsmittels, welches ein oxidierendes Agens oder ein reduzierendes Agens ist, umfaßt.
20. Verfahren gemäß Anspruch 19,
dadurch gekennzeichnet,
daß die Mischung auf eine Temperatur erhitzt wird, bei welcher eine isotrope Phase gebildet wird.



21. Elektronische Vorrichtung mit zumindest einem Material gemäß den Ansprüchen 1 bis 18, oder welches durch ein Verfahren gemäß den Ansprüchen 19 oder 20 hergestellt worden ist.

Revendications

1. Matériau cristallin liquide semi-conducteur, qui comprend un radical sel d'un mésogène formé en dopant le mésogène avec pas plus de 0,5 mole de dopant par mole de mésogène, le dopant étant un agent oxydant ou un agent réducteur.

2. Matériau selon la revendication 1, caractérisé en ce que la molécule de mésogène contient une partie aromatique.

3. Matériau selon l'une des revendications 1 ou 2, caractérisé en ce que le mésogène est un mésogène analogue à un disque.

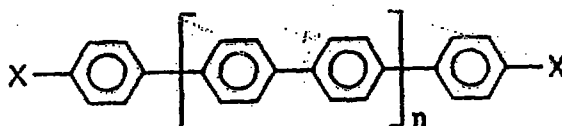
4. Matériau selon l'une des revendications précédentes, caractérisé en ce que le mésogène est un hexa-n-alkanoate de triphénylène ou un hexa-n-alcoxy-triphénylène.

5. Matériau selon la revendication 4, caractérisé en ce que le mésogène est 2,3,6,7,10,11-hexa-hexyloxy triphénylène.

6. Matériau selon la revendication 4, caractérisé en ce que le mésogène est 2,3,6,7,10,11-hexa-hexylthio-triphénylène.

7. Matériau selon la revendication 4, caractérisé en ce que le mésogène est 2,3,6,7,10,11-hexa-(paraundécyloxybenzoyloxy)triphénylène.

8. Matériau selon la revendication 2, caractérisé en ce que la molécule de mésogène comprend une partie polyaromatique ayant la formule :



dans laquelle X représente un groupe de chaîne terminale et n est un entier ayant une valeur d'au moins 1.

9. Matériau selon la revendication 8, caractérisé en ce que X représente un groupe alcoyle ou un groupe alcoxy.

10. Matériau selon la revendication 2, caractérisé en ce que la molécule de mésogène comprend au moins deux cycles aromatiques liés de façon à former une molécule analogue à une tige.

11. Matériau selon l'une des revendications 1 à 9, caractérisé en ce que le matériau est un polymère cristallin liquide, dans lequel un radical sel d'un mésogène est incorporé, soit dans la chaîne principale, soit dans une ou plusieurs chaînes latérales.

12. Matériau selon l'une des revendications précédentes, caractérisé en ce que le mésogène comprend un radical cation.

13. Matériau selon l'une des revendications précédentes, caractérisé en ce que le dopant est choisi dans le groupe comprenant le trichlorure d'aluminium, le tribromure d'aluminium, l'iode et le pentafluorure d'antimoine.



14. Matériau selon l'une des revendications précédentes, qui contient pas plus de 0,25 mole de dopant par mole de mésogène.
15. Matériau selon la revendication 14, qui comprend pas plus de 0,1 mole de dopant par mole de mésogène.
16. Matériau selon l'une des revendications précédentes, dans lequel la conductance du matériau cristallin liquide dans au moins une dimension est 1,1 fois plus grande que sa conductance dans une autre dimension.
17. Matériau selon la revendication 16, caractérisé en ce que la conductance du matériau cristallin liquide dans au moins une dimension est au moins dix fois plus grande que sa conduction dans une autre dimension.
18. Matériau selon l'une ou l'autre des revendications 16 ou 17, caractérisé en ce que le matériau est dans sa phase cristalline.
19. Procédé pour produire un matériau cristallin liquide semi-conducteur, qui consiste à mélanger un mésogène qui est capable de former un radical sel avec jusqu'à 0,5 fois autant de moles d'un dopant qui est un agent oxydant ou un agent réducteur.
20. Procédé selon la revendication 19, caractérisé en ce que le mélange est chauffé à une température à laquelle est formée une phase isotrope.
21. Dispositif électronique incorporant au moins un matériau selon l'une des revendications 1 à 18 ou qui a été produit par un procédé selon la revendication 19 ou la revendication 20.