



US009722130B2

(12) **United States Patent**
Chaudhari

(10) **Patent No.:** **US 9,722,130 B2**
(45) **Date of Patent:** **Aug. 1, 2017**

(54) **METHODS OF GROWING HETEROEPITAXIAL SINGLE CRYSTAL OR LARGE GRAINED SEMICONDUCTOR FILMS AND DEVICES THEREON**

(58) **Field of Classification Search**
CPC H01L 21/02603; H01L 21/02645; H01L 21/02653; H01L 21/02532; B82Y 40/00; C30B 11/12; C30B 29/06
See application file for complete search history.

(71) Applicants: **Karin Chaudhari**, Briarcliff Manor, NY (US); **Ashok Chaudhari**, Briarcliff Manor, NY (US); **Pia Chaudhari**, Briarcliff Manor, NY (US)

(56) **References Cited**

(72) Inventor: **Praveen Chaudhari**, Briarcliff Manor, NY (US)

U.S. PATENT DOCUMENTS

(73) Assignee: **Solar-Tectic LLC**, Briarcliff Manor, NY (US)

3,983,012 A 9/1976 Cohen
4,534,820 A * 8/1985 Mori C30B 11/12 11/7/58

(Continued)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 604 days.

OTHER PUBLICATIONS

(21) Appl. No.: **13/929,085**

Ross, "Controlling Nanowire Structures Through Real Time Growth Studies", Reports on Progress in Physics, Oct. 2010, pp. 1-21, vol. 73, IOP Publishing. UK & US.

(22) Filed: **Jun. 27, 2013**

(Continued)

(65) **Prior Publication Data**
US 2013/0284258 A1 Oct. 31, 2013

Primary Examiner — Matthew Song

Related U.S. Application Data

(63) Continuation of application No. 12/903,750, filed on Oct. 13, 2010, now Pat. No. 8,491,718, which is a (Continued)

(74) *Attorney, Agent, or Firm* — Carter Ledyard & Milburn LLP

(51) **Int. Cl.**
H01L 21/02 (2006.01)
H01L 31/18 (2006.01)

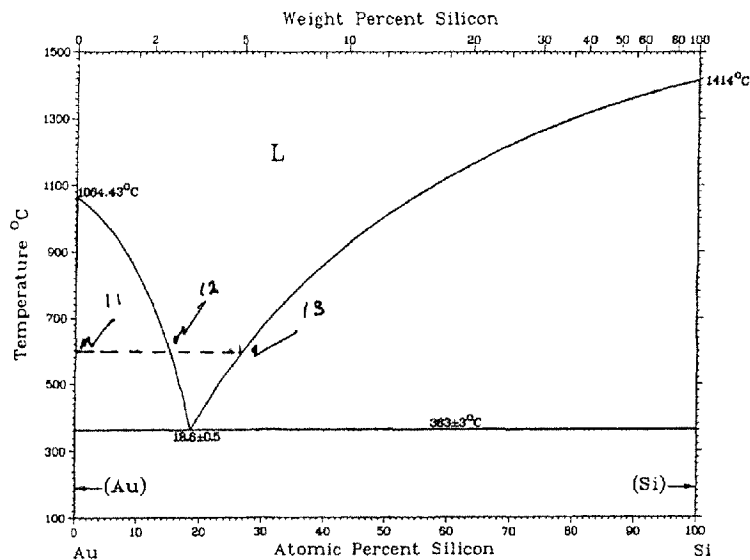
(Continued)

(57) **ABSTRACT**

(52) **U.S. Cl.**
CPC **H01L 31/1804** (2013.01); **C30B 11/12** (2013.01); **C30B 23/025** (2013.01); (Continued)

A method is disclosed for making semiconductor films from a eutectic alloy comprising a metal and a semiconductor. Through heterogeneous nucleation said film is deposited at a deposition temperature on relatively inexpensive buffered substrates, such as glass. Specifically said film is vapor deposited at a fixed temperature in said deposition temperature where said deposition temperature is above a eutectic temperature of said eutectic alloy and below a temperature at which the substrate softens. Such films could have widespread application in photovoltaic and display technologies.

31 Claims, 1 Drawing Sheet



Related U.S. Application Data

continuation-in-part of application No. 12/774,465, filed on May 5, 2010, now Pat. No. 9,054,249, which is a continuation of application No. 12/154,802, filed on May 28, 2008, now abandoned.

(51) **Int. Cl.**

- C30B 11/12** (2006.01)
- H01L 31/0236** (2006.01)
- C30B 25/02** (2006.01)
- C30B 29/06** (2006.01)
- C30B 23/02** (2006.01)
- C30B 25/18** (2006.01)
- H01L 31/0475** (2014.01)
- H01L 31/0216** (2014.01)
- H01L 31/0687** (2012.01)
- H01L 31/0725** (2012.01)

(52) **U.S. Cl.**

- CPC **C30B 25/02** (2013.01); **C30B 25/183** (2013.01); **C30B 29/06** (2013.01); **H01L 21/0256** (2013.01); **H01L 21/0262** (2013.01); **H01L 21/02422** (2013.01); **H01L 21/02425** (2013.01); **H01L 21/02439** (2013.01); **H01L 21/02488** (2013.01); **H01L 21/02532** (2013.01); **H01L 21/02546** (2013.01); **H01L 21/02557** (2013.01); **H01L 21/02595** (2013.01); **H01L 21/02598** (2013.01); **H01L 21/02603** (2013.01); **H01L 21/02623** (2013.01); **H01L 21/02625** (2013.01); **H01L 21/02645** (2013.01); **H01L 21/02653** (2013.01); **H01L 31/0216** (2013.01); **H01L 31/02363** (2013.01); **H01L 31/02366** (2013.01); **H01L 31/0475** (2014.12); **H01L 31/0687** (2013.01); **H01L 31/0725** (2013.01); **H01L 31/18** (2013.01)

(56)

References Cited

U.S. PATENT DOCUMENTS

4,717,688	A	1/1988	Jaentsch	
5,326,719	A	7/1994	Green et al.	
5,523,587	A	6/1996	Kwo	
5,544,616	A	8/1996	Ciszek et al.	
5,897,331	A *	4/1999	Sopori	H01L 21/2026 136/258
6,097,139	A *	8/2000	Tuck	H01J 1/304 313/309
6,429,035	B2	8/2002	Nakagawa et al.	
6,500,604	B1 *	12/2002	Dimitrakopoulos ...	B82Y 30/00 430/322
6,784,139	B1	8/2004	Sankar et al.	
7,087,113	B2	8/2006	Goyal	
7,129,154	B2	10/2006	Yi	
7,157,737	B2	1/2007	Voutsas et al.	
7,344,961	B2	3/2008	Romano et al.	
7,625,812	B2	12/2009	Choi et al.	
7,662,678	B2	2/2010	Xianyu et al.	
7,906,229	B2	3/2011	Goyal	
7,964,479	B2	6/2011	Iacopi et al.	
8,012,861	B2	9/2011	Im	
8,043,943	B2	10/2011	Maboudian et al.	
8,071,872	B2	12/2011	Atanackovic	
2005/0279274	A1	12/2005	Niu et al.	
2006/0009003	A1	1/2006	Romano et al.	
2006/0115964	A1 *	6/2006	Findikoglu	C30B 25/18 438/509
2006/0208257	A1	9/2006	Branz et al.	
2006/0255481	A1 *	11/2006	Pan	B82Y 10/00 438/584

2007/0004222	A1 *	1/2007	Wei	B82Y 30/00 438/775
2007/0044832	A1	3/2007	Fritzemeier	
2007/0096304	A1 *	5/2007	Kabir	B01J 23/755 257/734
2007/0286945	A1	12/2007	Lahinoor et al.	
2008/0090072	A1 *	4/2008	Findikoglu	C03C 17/3411 428/336
2008/0188064	A1 *	8/2008	Samuelson	B82Y 10/00 438/488
2008/0217622	A1	9/2008	Goyal	
2009/0183774	A1	7/2009	Atanackovic	
2009/0309104	A1	12/2009	Im	
2010/0096618	A1 *	4/2010	Iacopi	C30B 11/12 257/14
2010/0184276	A1	7/2010	Maboudian et al.	
2010/0279513	A1	11/2010	Niu et al.	
2011/0034339	A1	2/2011	Goyal	
2011/0062446	A1	3/2011	Goyal	
2012/0012166	A1	1/2012	Atanackovic	

OTHER PUBLICATIONS

Chaudhari et al. "Heteroepitaxial Silicon Film Growth at 600 C From an Al-Si Eutectic Melt", Thin Solid Films 518, Mar. 2010, pp. 5368-5371, Elsevier, US.

Fortuna and Li, "Metal-Catalyzed Semiconductor Nanowires: A Review on the Control of Growth Directions", Semiconductor Science and Technology, 2010, pp. 1-16, vol. 25, IOP Publishing, UK.

Badeshia et al., "Calculation of Crystallographic Texture due to Displacive Transformations", 2008, pp. 342-346, vol. 99, International Journal of Materials Research, Germany.

Teplin et al. "A Proposed Route to Thin Film Crystal Si Using Biaxially Textured Foreign Template Layers", National Renewable Energy Laboratory, Conference Paper, Nov. 2005, pp. 1-4, U.S. Dept. of Energy, US.

Kayes et al., "Comparison of the Device Physics Principle of Planar and Radial p-n Junction Nanorod Solar Cells", Journal of Applied Physics 97, 114302, Dec. 2005, pp. 1-11, America Institute of Physics, US.

Findikoglu et al., "Well-Oriented Silicon Thin Films with High Carrier Mobility on Polycrystalline Substrates", Advanced Materials, 2005, pp. 1527-1531, Wiley-VCH Verlag etc., Wernheim, DE.

Goyal et al., The Rabbits Approach: Using Rolling-Assisted Biaxially Textured Substrates for High-Performance YBCO Superconductors, MRS Bulletin, Aug. 2004, pp. 552-561, mrs.org Publications Bulletin, US.

Kodambaka et al., "Germanium Nanowire Growth Below the Eutectic Temperature", Science, May 2007, pp. 729-732, vol. 316, US.

Wenk and Van Houte, "Texture and Anisotropy", Reports on Progress in Physics, 2004, pp. 1367-1428, vol. 67, Institute of Physics Publishing, UK.

Hofmann et al. "Gold Catalyzed Growth of Silicon Nanowires by Plasma Enhanced Chemical Vapor Deposition", Journal of Applied Physics, Nov. 2003, pp. 6005-6012, vol. 94, No. 9, US.

Nast et al., "Aluminum-Induced Crystallization of Amorphous Silicon on Glass Substrates above and below the Eutectic Temperature", Applied Physics Letters, Nov. 1998, pp. 3214-3216, vol. 73, No. 22, American Institute of Physics, US.

Wang et al. "Epitaxial Growth of Silicon Nanowires Using an Aluminium Catalyst", Nov. 2006, pp. 186-189, vol. 1, Nature Publishing Group, US.

Goyal et al. "Low Cost Single Crystal-Like Substrates for Practical, High Efficiency Solar Cells", AIP Conference, 1997, pp. 377-394, US.

Lloyd et al. "Crystallographic Textures", Mineralogical Magazine, 1991, pp. 331-345, vol. 55, Mineralogical Society, UK.

Massalski et al. "Binary Alloy Phase Diagrams", 1990, pp. 425-431, vol. 1, 2nd. Ed., The Materials Information Society, US.

(56)

References Cited

OTHER PUBLICATIONS

Yue and Gu, "Semiconductor Eutectic Solar Cell", Dec. 1986, pp. 1-126, California University, Los Angeles, School of Engineering and Applied Science, US Department of Commerce, National Technical Information Service.

Kass et al., "Liquid Phase Epitaxy of Silicon: Potentialities and Prospects", Max Planck Institute, Stuttgart, DE., Physica, 129B, 1985, pp. 161-165, Elsevier, Holland.

Girault et al., "Liquid Phase Epitaxy of Silicon at Very Low temperatures", Montpellier, FR, Oct. 1976, pp. 169-177, Journal of Crystal Growth 37 (1997), Holland.

Herd et al., "Metal Contact Induced Crystallization in Films of Amorphous Silicon and Germanium", Jan. 1972, pp. 309-327, Journal of Non-Crystalline Solids 7 (1972), US.

Wagner and Ellis, "The Vapor-Liquid-Solid Mechanism of Crystal Growth and its Application to Silicon", Jun. 1965, pp. 1053-1064, vol. 233, Transactions of the Metallurgical Society of AIME, US.

Wagner and Ellis, "Vapor-Liquid-Solid Mechanism of Crystal Growth", Mar. 1964, pp. 89-90, vol. 4, No. 5, Applied Physics Letters, US.

Teplin et al., "Low-Temperature Silicon Hompepitaxy by hot-wire chemical vapor deposition with a TA filament", Journal of Crystal Growth, Science Direct, Jan. 4, 2006, vol. 287, pp. 2414-2418, Elsevier, US.

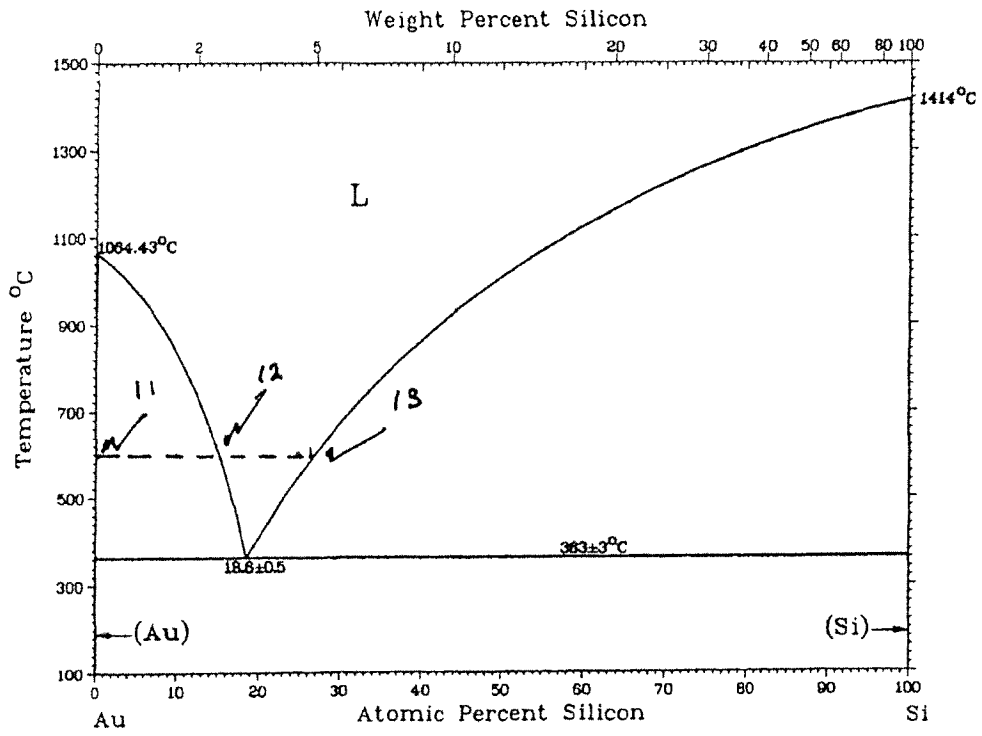
Rath J. K., "Low temperature polycrystalline silicon: a review on deposition, physical properties and solar cell applications", Solar Energy Materials & Solar Cells, vol. 76, 2003, pp. 431-487, Elsevier, US.

Uematsu et al. "Very-Low-Temperature Silicon Epitaxy by Plasma-CVD using SiH4-Ph3-H2 Reactants for Bipolar Devices", Apr. 1988, vol. 4, pp. L493-L495, Japanese Journal of Applied Physics, Japan.

Ferro, Gabriel et. el., VLS Growth of SiC Epilayers, HAL archives-ouvertes, Apr. 6, 2007, pp. 1-23, <https://hal.archives-ouvertes.fr/hal-00140374>, France.

Ferro, Gabriel et ano., Growth by a Vapour-Liquid-Solid Mechanism: A New Approach for Silicon Carbide Epitaxy, New. J. Chem., Jul. 7, 2004, pp. 889-896, vol. 28, The Royal Society of Chemistry and the Centre National de la Recherche Scientifique, UK.

* cited by examiner



**METHODS OF GROWING
HETEROEPITAXIAL SINGLE CRYSTAL OR
LARGE GRAINED SEMICONDUCTOR
FILMS AND DEVICES THEREON**

The present invention is a continuation of U.S. patent application Ser. No. 12/903,750, now U.S. Pat. No. 8,491,718 issued Jul. 23, 2013, which is a continuation-in-part of U.S. patent application Ser. No. 12/774,465, now U.S. Pat. No. 9,054,249 issued Jun. 9, 2015, which is a continuation of U.S. patent application Ser. No. 12/154,802, now abandoned, filed May 28, 2008 all of which are hereby incorporated by reference in their entirety.

REFERENCES CITED

U.S. Patent Documents

U.S. Pat. No. 4,717,688 1/1987 Jaentsch . . . 148/171
U.S. Pat. No. 5,326,719 7/1994 Green et al. . . 427/74
U.S. Pat. No. 5,544,616 8/1996 Ciszek et al. . . 117/60
U.S. Pat. No. 6,429,035 B2 8/2002 Nakagawa et al. . .
438/57
U.S. Pat. No. 6,784,139 B1 8/2004 Sankar et al. . . 505/230

Other Publications

Kass et al, "Liquid Phase Epitaxy of Silicon: Potentialities and Prospects", *Physica B*, Vol 129, 161 (1985)
Massalski et al, "Binary Alloy Phase Diagrams", 2nd edition, (1990), ASM International
Findikoglu et al, "Well-oriented Silicon Thin Films with High Carrier Mobility on Polycrystalline Substrates", *Adv. Materials*, Vol 17, 1527, (2005)
Teplin et al, "A Proposed Route to Thin Film Crystal Si Using Biaxially Textured Foreign Template Layers" Conference paper NREL/CP-520-38977, November 2005
Goyal et al., "The RABiTS approach: Using Rolling-assisted Biaxially Textured Substrates for High-performance YBCO Superconductors," *MRS Bulletin*, Vol. 29, 552, (2004)
Nast et al, "Aluminum Induced Crystallization of Amorphous Silicon on Glass Substrates Above and Below the Eutectic Temperature", *Appl. Phys. Lett.*, Vol 73, 3214, (1998)
Girault et al, "Liquid Phase Epitaxy of Silicon at very low Temperatures", *J. Crystal Growth*, Vol 37, 169 (1977)
Kayes et al, "Comparison of the Device Physics Principles of Planar and Radial p-n junction Nanorod Solar Cells", *J. Appl. Phys.*, Vol 97, 114302, (2005)

FIELD OF THE INVENTION

The present invention is related to producing large grained to single crystal semiconductor films, such as silicon films, for producing articles such as photovoltaic and other electronic devices.

FEDERAL FUNDING

None

BACKGROUND OF THE INVENTION

It is widely known that radiation from the sun striking earth provides enough energy to supply all of mankind's

needs for energy for the indefinite future. Such a source of energy can be clean and environmentally benign.

It is also widely known that global warming is associated with the use of fossil fuels, such as coal, oil, and natural gas. It is accepted by the scientific community that global warming can have severe adverse effects around the planet. There are numerous efforts around the world, combined with a sense of urgency, to cut down emissions from the usage of fossil fuels. A dominant factor in favor of the continual use of fossil fuels is their cost per unit of available energy. If, for example, the cost of producing photovoltaic cells can be reduced by a factor of approximately three while maintaining efficiency of conversion, the photovoltaic technology would become cost competitive with fossil fuels.

A major cost component in photovoltaic cells is the cost of the substrate on which the semiconductor film capable of converting sunlight into electricity is placed. The most widely used substrate is single crystal silicon (Si). These substrates developed for the microelectronics industry have been modified for application in photovoltaic technology. If a silicon film could be deposited on an inexpensive substrate, such as glass, and with comparable quality as that found in silicon single crystals used in the microelectronics industry, the cost of photovoltaic technology would drop significantly.

Epitaxial growth of thin films is a very well established process. It has been investigated by hundreds of researchers. Epitaxial deposition provides a very viable way of growing very good quality films. Many single crystal semiconductors and insulator surfaces are used to study the epitaxial growth of metallic films; for example, the growth of silver on silicon, sapphire, or a mica surface. Epitaxial metallic films have also been grown on other metallic films, such as gold on silver. In contrast to metals, semiconductors, such as silicon, are difficult to grow epitaxially. For example, heteroepitaxial films of silicon have been successfully grown only on sapphire but at temperatures that are relatively high for the applications we disclose here, such as the growth of silicon on glass substrates.

In order to take advantage of highly textured large grained films for photovoltaic technology two problems need to be solved: inexpensive growth of high quality films and the availability of an inexpensive substrate on which desirable properties can be achieved. Here, we disclose a method for growing semiconductor films, such as silicon, satisfying the two requirements listed above and suitable for photovoltaic technology and other electronic applications.

The thermodynamic stability and formation temperature of two or more elements is described by a composition versus temperature diagram, called a phase diagram. In this invention we shall make use of phase diagrams. These phase diagrams are available in the scientific literature (Massalski et al). The phase diagram provides information on the behavior of different phases, solid or liquid as a function of temperature and composition. For example, the liquidus in a simple binary eutectic system, such as Au and Si, shows how the relative composition of the liquid and solid, it is in equilibrium with, changes with temperature. It is therefore possible to choose an average composition, different from the eutectic composition, and cool the mixture in such a way as to precipitate out one phase or the other. If the composition is chosen to be richer in silicon than the eutectic composition then on cooling through the liquidus boundary between the single phase liquid and the two phase liquid plus solid, silicon will nucleate and form a solid phase. If on the other hand it is gold rich relative to the eutectic composition the first solid phase to nucleate is gold rather than silicon.

At and below the eutectic temperature the two components, in this case, Au and Si solidify from the liquid phase to phase separate into the two components Au and Si. The interface energy between the two components is generally positive and therefore drives the two components to aggregate into distinct phases with a minimum of surface area between the two rather than a fine mixture of the two. There is, however, the energetics of two other interfaces to consider also: one with the substrate and the other with vacuum or gas. In considering energetics it is not only the chemical interaction of the metal or Si with the substrate that is important but also its crystallographic orientation, for the surface or interface energy depends upon orientation of the grains. Another concern is the difference in lattice match between the nucleating film and the substrate which can lead to strain induced energy that is minimized by either inducing defects or not growing uniformly in thickness across the substrate surface. These factors determine if silicon is likely to deposit on the substrate (heterogeneous nucleation) or nucleate and forms small crystals in the liquid (homogeneous nucleation).

An advantage of using eutectics compositions is that the eutectic temperature is lower than the melting temperature of the constituent elements. For example, the eutectic temperatures of Au, Al, and Ag with Si are 363, 577, and 835 degrees Centigrade ($^{\circ}$ C.), respectively. In contrast the melting temperatures of the elements are 1064, 660, and 961 $^{\circ}$ C., respectively. The melting temperature of silicon is 1414 $^{\circ}$ C. The eutectics then offer the possibility of nucleating a silicon crystal from the liquid far below the temperature at which pure liquid silicon crystallizes. By a proper choice of the substrate surface exposed to the nucleating silicon, it is possible to nucleate and grow single crystal or large grained silicon films.

We have discussed silicon eutectics using elements such as Au, Ag, and Al. However, it is possible to replace the elements by silicon based compounds. For example, the compound nickel silicide forms a eutectic with Si. There are numerous other examples of silicide compounds forming a eutectic with Si (Massalski et al). An advantage of using a silicide is that frequently the electrical contact of the silicide with silicon has very desirable properties, such as a good ohmic contact or a Schottky barrier. Some silicides are also known to have an epitaxial relationship with silicon. In this case, by appropriately choosing either a silicide rich or silicon rich melt either the silicon can be induced to grow epitaxially on the silicide or the silicide on silicon. A disadvantage in this approach is the eutectic temperature, which is generally high.

Low temperature solutions can also be formed with some elements, For example, gallium (Ga) and Si have a eutectic temperature of less than 30 $^{\circ}$ C., very close to that of the melting point of Ga. There are other elements, such as indium or tin that form low temperature liquid solutions with silicon. Si can be nucleated from these solutions at very low temperatures relative to pure silicon (Girault et al, Kass et al). These temperatures are sufficiently low that it opens up the possibility of using organic materials as substrates on which large grained to single crystal films can be grown. While this is an advantage, there is also a serious disadvantage; at these low temperatures, the silicon film can contain defects and hence are not very useful as a photovoltaic material. However, these very low temperature deposits can be used to initiate the nucleation of a very thin silicon film, which is subsequently thickened by using higher temperature processes to optimize its photovoltaic properties.

The choice of a particular system (phase diagram) is not only determined by temperature and energetics of the interfaces, but also by the solubility of the second element in Si. It is desirable to have precise control of the doping of Si in order to optimize its semiconductor properties for photovoltaic applications. It is also important to select the composition of the substrate and temperature of processing such that there is minimal or no chemical interaction between the silicon film and the surface of the substrate on which it is being deposited.

From the preceding description, we can extract five common points which are relevant to this invention. First, one end of the phase diagram always has the semiconductor we wish to nucleate and use to produce a film, we have used silicon in the preceding examples but it could be germanium or a compound such as gallium arsenide or cadmium selenide. Second, the thermodynamically predicted concentration of the second element or phase in the semiconductor is minimal. If there is solubility then it must be a desirable dopant. For example aluminum (Al) in silicon behaves as a p-type dopant and experience in the semiconductor industry has shown that trace amount of Al can be desirable. Third, the liquidus curve has the highest temperature on the semiconductor side. In other words, the melting point of the semiconductor is greater than the liquidus for all compositions in equilibrium with the semiconductor. Fourth, the homogeneous nucleation energy of silicon crystal from the melt is greater than that for heterogeneous nucleation on the substrate. This latter condition promotes heterogeneous nucleation. And, fifth, the temperature for epitaxial growth is low enough to use inexpensive substrates such as glass but high enough to promote a good quality silicon film. For example, a growth temperature above approximately 550 degrees Centigrade (550 $^{\circ}$ C.) is desirable to make a good quality silicon film. The softening temperature of ordinary glasses is around 600 $^{\circ}$ C. The softening temperature of borosilicate glasses is higher. However it is not high enough to use conventional deposition temperature of greater than 750 degrees Centigrade for silicon on insulator, such as a sapphire substrate.

In order to take full advantage of the invention disclosed here the semiconductor material has to be deposited on a substrate material which is inexpensive, and the surface of which enables heterogeneous nucleation and growth. In the following we shall discuss two specific methods for producing substrates suitable for heterogeneous deposition of films for photovoltaic technology. Both of these methods have been described in the scientific literature and we do not claim to invent them. We include them here for completeness.

The use of rolled and textured Ni and Ni-alloy sheets has been proposed as substrate material for superconducting films and, more recently, for films for photovoltaic devices (Findikoglu et al). In order to facilitate the growth of epitaxial superconducting films on such substrates, there have been two approaches described in the scientific literature: in one the sharp rolling texture produced in a rolled and annealed Ni alloy is used as a template on which various epitaxial buffer layers are deposited followed finally by an epitaxial film of a high temperature cuprate superconductors (Goyal et al). In the second approach (Findikoglu et al), the nickel ribbon is used as a substrate for ion beam assisted deposition of a wide variety of highly textured ceramics, for example, magnesium oxide (MgO). The ion beam aligns the growing MgO film, which provides a template for the subsequent deposition of the cuprate superconductor. The latter approach is not limited to using metal tapes but can be

extended to other inexpensive substrates such as glass (Teplin et al). It has been found that texture can also be induced in MgO by depositing the film on a substrate that is inclined to the normal from the oncoming vapor of MgO.

One limitation of the use of glass as a substrate has been its softening temperature, which is generally lower than the conventional processing temperatures required for the growth of large grained or single crystal films of silicon. With the method of depositing silicon films at low temperatures, described in this invention, the use of buffered glass becomes an option for we can deposit highly textured and large grained silicon on MgO at or below the softening temperature of glass. Similarly, researchers have grown crystalline aluminum oxide (Al₂O₃) on inexpensive substrates (Findikoglu et al). We shall use MgO and Al₂O₃ as illustrative examples. However, it is understood to those skilled in the art that a variety of other materials can also work. Both Findikoglu et al and Goyal et al describe other buffer layers, including conducting ceramic layers, such as TiN.

OBJECTS OF THE INVENTION

It is an object of the present invention to provide single crystal or highly textured relatively large grained good quality semiconductor films and, in particular silicon films, for photovoltaic technology or other semiconductor devices, such as field effect transistors used, for example, in displays.

It is yet another object of this invention to provide single crystal or highly textured relatively large grained good quality semiconductor films and, in particular silicon films, at low temperatures. For example, if silicon films are used, the growth temperature is between 450 and 750 degrees Centigrade.

It is yet another object of this invention to provide single crystal or highly textured relatively large grained good quality semiconductor films and, in particular silicon films, on inexpensive substrates, for example, substrates such as glass on which buffer layers such as MgO and/or Al₂O₃ have been deposited.

SUMMARY OF THE INVENTION

In accordance with one aspect of the present invention, the forgoing and other objects can be achieved by alloying a semiconductor and, in particular silicon, with elements or compounds that form an eutectic system, and increasing slowly the concentration of the semiconductor, such as silicon, through the liquidus line to reach the two phase region in which the semiconductor, in particular silicon, nucleates out of the melt and on the surface of a substrate.

In accordance with another aspect of the present invention, the forgoing and other objects can be achieved by alloying a semiconductor and, in particular silicon, with elements or compounds that form an eutectic system, and increasing slowly the concentration of the semiconductor, such as silicon, through the liquidus line to reach the two phase region in which the semiconductor, in particular silicon, nucleates on the surface of a substrate to produce a highly textured relatively large grained or single crystalline film.

In accordance with yet another aspect of the present invention, the forgoing and other objects can be achieved by alloying a semiconductor and, in particular silicon, with elements or compounds that form an eutectic system, and increasing slowly the concentration of the semiconductor, such as silicon, through the liquidus line to reach the two

phase region in which the semiconductor, in particular silicon, nucleates on the surface of a substrate made of a buffered tape in which texture is produced by mechanical deformation and the buffer layers are epitaxial to the texture of the metal tape. The buffer layer exposed to the melt comprises of compounds, such as Al₂O₃ or MgO.

In accordance with yet another aspect of the present invention, the forgoing and other objects can be achieved by alloying a semiconductor and, in particular silicon, with elements or compounds that form an eutectic system, and increasing slowly the concentration of the semiconductor, such as silicon, through the liquidus line to reach the two phase region in which the semiconductor, in particular silicon, nucleates on the surface of a substrate made of a buffered tape, a glass substrate, or any other material suitable for inexpensive manufacture of photovoltaic cells in which strong texture is produced by ion beam assisted deposition. The final layer, which is exposed to the silicon melt, comprises of compounds, such as Al₂O₃ or MgO.

In accordance with still another aspect of the present invention, the forgoing and other objects can be achieved by using a solid phase composition comprising a semiconductor and, in particular silicon, with elements or compounds that form an eutectic system, and in which a thin film of the element or compound is deposited first followed by the semiconductor, such as silicon, and depositing at a temperature where the semiconductor atoms diffuse through the element or compound to heterogeneously nucleate on the substrate and propagate this crystallinity to the semiconductor film remaining on top of the element or compound.

The method of manufacture of materials suitable for photovoltaic technologies described in this invention are much less expensive in the conversion of sunlight into electricity than those practiced in the prior art.

BRIEF DESCRIPTION OF DRAWINGS

FIG. 1 shows the phase diagram of the eutectic system Au—Si, taken from the literature (Massalski et al). The melting points of the two elements Au and Si, as well as the eutectic temperature are shown in the figure. The eutectic composition is also indicated. The liquidus line, which defines the boundary between the liquid gold-silicon alloy and solid silicon and a gold-silicon liquid alloy, and on the silicon rich side of the phase diagram, is marked. The figure also shows the change in phases as the composition is changed by depositing silicon on a film of gold held at constant temperature. As the silicon is evaporated on to the gold film, the film comprises of gold solid and a liquid gold-silicon alloy which changes from the point marked by **11** towards **12**. Further deposition of silicon results in the film entering the liquid phase region between the points marked **12** and **13**. As the silicon deposition continues beyond the point **13**, the liquidus boundary, solid silicon nucleates from the liquid which is in equilibrium with a silicon-gold liquid alloy. The solid silicon is deposited on a MgO substrate, forming a highly textured and relatively large grained heterogeneously nucleated film. The thickness of the solid silicon film increases till the deposition is stopped. As it cools Si continues to deposit from the melt while the Au—Si liquid solution becomes richer in gold. This process continues till the eutectic temperature is reached, at which point the liquid solidifies and phase separates into gold and silicon solids.

We have used the phase diagram of the Au—Si eutectic. The Al—Si eutectic is very similar. Here we can heteroge-

neously nucleate silicon from the Al—Si melt on a single crystal sapphire substrate to form a single crystal heteroepitaxial silicon film.

DETAILED DESCRIPTION OF THE INVENTION

As described above, we have disclosed a method to produce low cost single crystal or large grained epitaxially aligned good quality semiconductor films, in particular silicon, for photovoltaic technology. We have also suggested the use of tapes or glass slabs as substrate materials. The tapes provide strong texture on which buffer layers suitable for silicon growth are present. Our method can produce silicon epitaxy at substantially lower temperatures than those commonly practiced, hence not only minimizing interaction with the surface of the substrate but also enabling the use of glass substrates.

We shall be using the eutectics of silicon with gold and aluminum in describing the details of the invention. It is, however, understood that one skilled in the art can extend the methodology to other semiconductors such as germanium, gallium arsenide, or the cadmium selenide class of photovoltaic materials.

FIG. 1 shows the phase diagram of the eutectic system Au—Si. The eutectic composition is nominally 18.6 atomic percent pct Si and the rest being gold. A thin gold film is first deposited on the buffered substrate. This is followed by silicon deposition. As the silicon concentration increases the film first forms a two phase mixture of gold and liquid gold-silicon. The composition of the latter is determined by the choice of the deposition temperature. With further increase of silicon, the liquid phase region, marked **12**, is reached and the remaining gold is dissolved. With still further increase of the amount of silicon, the second liquidus phase boundary, marked **13**, is reached and subsequent deposition of silicon atoms results in a solid phase of silicon in equilibrium with the silicon-gold liquid. If the substrate surface is suitably chosen, for example MgO crystals, the solid silicon nucleates heterogeneously onto the surface. The choice of the temperature of deposition is determined by balancing two considerations: quality in terms of defects of the epitaxial film; too low a temperature or too rapid a growth rate of the film at that temperature can introduce defects versus too high a temperature when chemical interaction or mechanical integrity of the substrate limit the usefulness of the material.

We have started with vapor deposition of the metallic film and added silicon to it to traverse the phase diagram from point marked **11** in the figure. However, the metallic element and silicon can be co evaporated to reach any concentration between the points marked **12** and **13** in the figure and subsequently silicon added to reach the desired thickness, before cooling to room temperature.

When the desired thickness of the silicon film is obtained, the substrate with the film is cooled to room temperature. Even though the amount of gold required to catalyze a silicon film is small, it can be further reduced by etching the gold away, for example, by using iodine etch, available commercially. This gold can be recycled

EXAMPLES OF THE INVENTION

The following non-limiting examples are used as illustrations of the various aspects and features of this invention.

Example 1

A good high vacuum system with two electron beam guns, is used to deposit gold and silicon independently. A glass

substrate coated with ion beam assisted deposited MgO film is held at temperatures between 575 and 600° C. These are nominal temperatures. It is understood to one skilled in the art that lower or higher temperatures can also be used depending upon the softening temperature of the glass substrate or the reaction kinetics of either gold or silicon with the metallic tape or its buffer layers when used as substrates. A thin gold film of approximately 10 nm thickness is deposited first. This is followed by a silicon film deposited at a rate of 2 nm per minute on top of the gold film. The ratio of the thickness of the gold and silicon films is chosen such that the final composition ensures that a point, marked **13**, in FIG. 1 is reached. This point lies at the boundary between the two phase region of solid Si and a liquid Si—Au mixture. For example, for a 10 nm gold film followed a 100 nm silicon film satisfies this condition. Additional silicon film nucleates heterogeneously on the MgO surface to form the desired thin film. The film can now be cooled to room temperature, where the film now comprises of two phases: gold and a relatively large grained and highly textured film of silicon on MgO.

By relatively large grained it is understood to imply a grain size larger than would have been achieved if a silicon film had been deposited under the same conditions but without Au. In the example discussed above the crystallographic texture is strongly [111]. Instead of an insulating substrate such as MgO, it is possible to choose stable and electrically conducting nitrides, such as TiN.

The gold diffuses to the surface of the silicon film, driven by its lower surface energy relative to the silicon surface. The film is etched in a solution, such as a commercially available iodine based chemical, which removes the gold from the two phases, gold and silicon, leaving behind a silicon film.

This silicon film can now be used as the surface on which a thicker silicon film appropriately doped to form a p-n junction, suitable for applications such as photovoltaics, can be deposited. Alternatively, the thin silicon film can be used for heteroepitaxial deposition of other semiconductors, which might be more efficient convertors of sunlight to electricity.

We have used two electron beam guns as an illustrative example. It is understood to one skilled in the art that other methods such as a single gun with multiple hearths, chemical vapor deposition, thermal heating, or sputtering can also be used.

Example 2

A good high vacuum system with two electron beam guns is used to deposit aluminum and silicon independently. A glass substrate or a Ni based substrate coated with a buffer layer of Al₂O₃ is held at temperatures between 600 and 615 degree ° C. These are nominal temperatures. It is understood to one skilled in the art that lower or higher temperatures can also be used depending upon the softening temperature of the glass substrate or the reaction kinetics of either aluminum or silicon with the metallic tape or its buffer layers when used a substrates. The eutectic Al—Si is used instead of the Au—Si example above. A thin Al film 6 nm thick is deposited on the Al₂O₃ followed by a 100 nm thick silicon deposition, and as described in example 1, above, the two phase region comprising of solid silicon and a liquid Si—Al mixture is reached. The deposition is stopped and the sample is slowly cooled to room temperature. Aluminum diffuses through the silicon film, driven by its lower surface energy relative to silicon. The silicon film is heteroepitaxially

aligned by the Al_2O_3 surface. The aluminum film on the surface can be etched chemically by well known processes to leave behind a silicon film. The surface of this film can now be used for further growth of epitaxial films either for photovoltaic devices or for field effect transistors.

We note, as stated earlier, that silicon can be grown epitaxially on sapphire but at temperatures higher than 750°C . This is a well established commercial process. However, in the absence of aluminum, silicon deposition at, say, 600°C . produces a fine grained film rather than a heteroepitaxial film, as described above.

Example 3

We describe in this example how different methods of deposition can be combined to take advantage of highly textured films as described in example 1, above. The Si film produced from the deposition of example 1 is etched to remove the Au and then placed back into the vacuum chamber and $\text{p}^+\text{-Si}$ is deposited on this film. This latter layer serves two purposes: it provides a conducting layer for a photovoltaic device to be subsequently built on it and can be the starting point for a variety of differently configured photovoltaic devices as, for example, a nanowire photovoltaic device. Here a 2-3 nm thick gold film is deposited on the silicon using an electron gun. This 2-3 nm thick gold film breaks up into nanoparticles and is the starting point used by a number of investigators to use chemical vapor deposition to grow nanowires and use these nanowires for photovoltaic devices. The difference is that we show how an inexpensive buffered glass can be used rather than a relatively expensive single crystal Si substrate.

A second possibility is to deposit a Au film of thickness 5 nm as islands on a MgO buffered glass substrate, using lithographic or other means known in the art. A heavily doped silicon (p^+ or n^-) film is now deposited on the surface followed by a p - or n -type silicon using electron beam deposition, as described in example 1. The thickness of the heavily doped film is in the micron range whereas the lightly doped film is of the order of 100 nm. The deposition process is now changed and chemical vapor deposition is used for subsequent deposition of suitably doped films of silicon, practiced in the art to grow silicon nanowire photovoltaic devices. The heavier doped silicon film serves the purpose of a conducting layer. Using gold islands has the advantage of controlling the nanowires diameter and length in order to maximize the efficiency of the photovoltaic cell (Kayes et al). Instead of using the insulating MgO buffer layer, a conducting material such as TiN can be used.

Example 4

We describe how different methods of deposition and temperature can be combined to take advantage of films grown as described in Examples 1 and 2, above to produce desirable device structures. Instead of depositing the Al and Si films described in Example 2 above, by two electron beam heated sources in a vacuum, we deposit the Si by decomposition of silane using a chemical vapor deposition chamber. This is a well known industrial process. As in Example 2, we deposit a 6 nm thin film of Al on to a sapphire substrate held at 600°C . We then introduce silane gas into the chamber. At these temperatures, the silane decomposes to form a Si film which reacts with the Al to produce a eutectic solution and when this solution is saturated with Si (the equivalent of point marked 13 in FIG. 1 for an Au—Si alloy) the Si precipitates to heterogeneously nucleate to form

an epitaxial film on the surface of the sapphire substrate. This film is continuous and can be doped by adding borane or phosphene gases to silane to obtain p or n type semiconductor behavior. This film can now be used as a basis to construct thin film photovoltaic cells or, alternatively, grow nanowires of Si on top of it by simply lowering the temperature of the substrate below the eutectic temperature of Al—Si (577°C .). For example, if the temperature of deposition is 500°C ., Si nanowires will grow on top of the Si film. The Al particles that precipitate out of the Al—Si solution once the temperature of the substrates is below the eutectic temperature now catalytically reduce the silane gas to form nanowires, as described in the literature. These nanowires can be used to build electronic devices, including photovoltaic cells.

While the principles of the invention have been described in connection with specific embodiments, it should be understood clearly that the descriptions, along with the examples, are made by way of example and are not intended to limit the scope of this invention in any manner. For example, a variety of suitable substrates different from the examples given above can be utilized or a different variety of deposition methods and conditions can be employed as would be understood from this invention by one skilled in the art upon reading this document.

The invention claimed is:

1. An electromagnetic device comprising:

a substrate,

a thin metal film on said substrate, said thin film being between 2-10 nm thick; and

a semiconductor film deposited on said substrate, said semiconductor film being deposited from a eutectic alloy at a constant temperature, said constant temperature being above a eutectic temperature of said eutectic alloy, wherein said constant temperature is within a semiconductor growth temperature, said semiconductor growth temperature permitting growth of defect-free semiconductor film.

2. The device of claim 1, wherein the substrate is one of a group consisting of metal tapes, glass, and ceramic.

3. The device of claim 1, wherein said substrate has a buffer layer.

4. The device of claim 3, wherein said buffer layer is comprised of a nitride, Al_2O_3 or MgO.

5. The device of claim 4, wherein said nitride is Titanium Nitride.

6. The device of claim 1 wherein, said semiconductor-growth temperature is above 550 degrees Centigrade.

7. The device of claim 1 wherein, said semiconductor-growth temperature is above 450 degrees Centigrade.

8. The device of claim 1 wherein the eutectic alloy comprises a semiconductor and a metal.

9. The device of claim 8 wherein, said semiconductor is one of a group consisting of germanium, gallium arsenide, gallium nitride and cadmium selenide.

10. The device of claim 8 wherein, said metal is one of a group consisting of gold, aluminum, nickel and silver.

11. The device of claim 8 wherein, said metal is one of a group of-indium and tin.

12. The device of claim 1 wherein said substrate is organic.

13. The device of claim 1 wherein said semiconductor film is a heteroepitaxial film.

14. The device of claim 1 wherein said substrate is a single crystal.

15. The device of claim 1 wherein said substrate is sapphire.

11

16. The device of claim 1 wherein said semiconductor film is a single crystal.

17. The device of claim 1 wherein said semiconductor film is textured.

18. The device of claim 1, wherein the semiconductor film is p type.

19. The device of claim 1, wherein the semiconductor film is n type.

20. The device of claim 1, wherein the semiconductor film is used as the surface on which a thicker film is deposited epitaxially.

21. The device of claim 20, wherein said thicker film is an n-type.

22. The device of claim 1, wherein said semiconductor film is deposited by vapor phase, liquid phase, and solid phase.

23. The device of claim 1, wherein said substrate is a heated substrate.

24. The device of claim 1, wherein said semiconductor film is deposited at a temperature greater than 750° C.

25. The device of claim 1, wherein said device has a Schottky barrier.

26. The device of claim 1 wherein the semiconductor film is composed from a material of one of a group consisting of Class IV, Class III-V and Class II-VI elements.

27. The device of claim 26 wherein the material is gallium arsenide.

12

28. The electromagnetic device of claim 1 wherein once the desired thickness of said semiconductor film is obtained, the substrate with said semiconductor film is cooled to room temperature.

29. An electromagnetic device comprising:
a substrate;
a thin metal film on said substrate, said thin metal film being between 2-10 nm thick; and
a semiconductor film deposited onto said thin metal film, said semiconductor film being deposited on said thin metal film at a deposition temperature, said deposition temperature being a constant temperature, said semiconductor and said thin metal film forming a eutectic liquid; at said constant temperature, increasing concentration of said semiconductor such that the eutectic liquid becomes saturated with said semiconductor and said semiconductor nucleates from said eutectic liquid to form an epitaxial semiconductor film on the substrate.

30. The device of claim 29 wherein the metal is removed by etching.

31. The device of claim 29 wherein said constant temperature is between a eutectic temperature of said eutectic liquid and below a softening temperature of said substrate.

* * * * *