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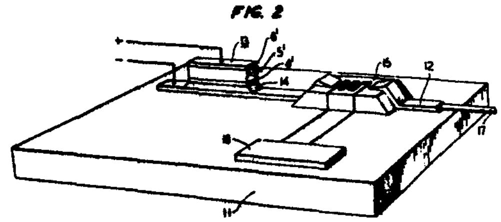
(54) **Devices including epitaxial layers of dissimilar crystalline materials and a method for selecting these materials for compatible epitaxial growth.**

(57) A device includes a layer (12) of one material epitaxially grown on another material (11). The materials have lattice constants which are in the ratio of an integer other than unity. For example one material (12) may be a semiconductor and the other a garnet (11). Thus magneto-optic (15) and electro-optic (13) devices can be combined on the same substrate to form integrated-optics devices.

FIG. 2



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DEVICES INCLUDING EPITAXIAL LAYERS OF DISSIMILAR CRYSTALLINE MATERIALS

The invention relates to devices including a first crystalline layer and a second crystalline layer epitaxially formed on at least a portion of the first layer.

Epitaxial growth of crystals will be understood to mean growth in which crystal line structure of one crystal layer extends smoothly into an adjacent crystal line structure of a second layer. In the prior art, only materials the lattice constants of which were equal or nearly equal were thought to be suitable for epitaxial growth.

The purpose of epitaxial crystal growing has been to provide extremely high quality crystals comprising layers of different chemical composition, for use in transistors, other semiconductor devices and integrated optics devices. It has been found that nonepitaxial crystal growth produces crystals with cracks, voids and other defects that impair the operation of these devices and result in their eventual failure.

Because nonepitaxial crystals were unsatisfactory, and epitaxial growth was thought to be restricted to combinations of materials with lattice constants that matched exactly or nearly so, the prior art was unable to combine chemical substances that, otherwise, could offer promise of improved performance in a wide variety of applications. For example, in the field of integrated optics, it has not previously been possible to combine III-V compounds for semiconductor devices and garnets and other magnetically suitable materials, and therefore it has not been possible to combine magnetic and electric devices on the same substrate.

One prior art method of combining materials of different lattice constants is disclosed in U.S. Patent No. 4,032,951, that discloses a method of epitaxial growth in which a layer of graded chemical composition forms a transition zone between two crystals of different lattice constants.

With the present invention as claimed, materials can be combined which were not previously considered compatible for use in epitaxially grown devices. For example, it is possible to combine semiconductor and garnet layers in a single device. It is also possible to combine, say, electro-optic devices and magneto-optic devices on a single substrate to form integrated-optics devices.

In the manufacture of electrical devices, also, the method taught by this invention will offer better choices of the materials. It is to be understood, therefore, that although the invention is described in the context of materials favourable for integrated optics, it has general application to crystalline materials when compatibility of epitaxially grown layers is desired.

Some embodiments of the invention will now be described by way of example with reference to the accompanying drawings of which:-

FIG. 1 shows an injection diode laser constructed according to the invention;

FIG. 2 shows a pictorial view of an integrated optical circuit including magnetic and optical devices;

FIG. 2A shows a section through FIG. 2; and

FIG. 3 shows a plot of the lattice constants of the iron, aluminium and gallium garnets against ionic radius of the added rare-earth element.

As an illustration of a device constructed according to the invention, consider the double heterostructure injection diode laser shown in FIG. 1, in which a first crystalline layer, garnet substrate 1, which is suitable for magneto-optic devices, has an epitaxially grown second crystalline layer of an n-type III-V semiconductor 2 that is conductive and serves both as the n-buffer layer and as one contact. The double heterostructure of the diode laser includes an active region 3, p-cladding layer 4, p^+ layer 5 and contact 6 in conventional fashion.

Illustratively, substrate 1 is Yttrium Aluminum Garnet (YAG) having a lattice constant of 12 Angstroms and the III-V compound of layer 2 is AlInAs, compounded to have a lattice constant of 6 Angstroms and an energy gap of .68 eV, capable of emitting radiation at 1.82 μm.

In FIG. 2, an integrated-optics device for generating an optical carrier, modulating the carrier and transmitting the modulated carrier into a fiber-optic waveguide is shown in which substrate 11 and thin film waveguide 12 are formed of a garnet and a III-V compound respectively, with lattice constants adjusted for an integral ratio.

Laser 13 is another version of the semiconductor injection laser known as the twin-guide laser, in which laser light generated in active layer 14 is coupled to waveguide 12 below, through a tapered transition. Waveguide 12 also serves as one of the electric contacts of the laser. Layers 4', 5', and 6' are equivalent to layers 4, 5, and 6 in FIG. 1. The radiation from laser 13 then travels through waveguide 12 into and out of a magneto-optic switch 15 which is formed from a garnet-based material directly on garnet substrate 11. The method of the coupling using tapered edges of the films and the magneto-optic switch described here are earlier inventions of the present inventor (U.S. Patent 3,764,195 and 4,806,226). The laser, switch and waveguides of various shapes can be grown on the garnet substrate by the method of "selective growth" which is well known in epitaxial technology. Switch 15, controlled by electronics logic circuit 16, illustratively a time-division multiplexer that combines input bit streams (arriving on contacts not shown), forms a modulated radiation beam that continues through waveguide 12 to optical fiber 17 for transmission.

FIG. 2A shows a section along waveguide 12 through the centerline of devices 13 and 15 and of waveguide 12, indicating by cross-hatching the garnet and semiconductor components of the device. In particular, active region 14 of laser 13 and waveguide 12 are both formed from III-V semiconductors (differently doped), and megneto-optic switch 15 and substrate 11 are formed from garnet-based compounds.

FIG. 3 shows a graph plotting the lattice constants of all the iron, gallium and aluminum garnets against ionic radius of the added rare-earth element. Individual elements are indicated at the appropriate ionic radius, and the positions of three well-known garnets are indicated by circles - GGG (Gd - Ga - Garnet), YAG (Y - Al - Garnet) and LuAG (Lu - Al - Garnet).

The graph provides the numerical value of the lattice constant of a particular garnet compound, so that an appropriate III-V semiconductor may be found to provide an integral ratio of lattice constants. The method of calculating the composition of a III-V compound that has a particular lattice constant is a straightforward application of Vegard's law and is well known in the art. (See Physics of III-V Compounds, Madelung and Meyerhofer, Wiley, N.Y., 1964, page 272).

As an example, combinations of a garnet substrate with a III-V semiconductor compound are indicated in Table I, which shows for each of three garnets the lattice constants of the garnet, a ternary or quaternary III-V semiconductor compound with lattice constant half that of the garnet, and the wavelength of light emitted by a laser formed from that III-V compound. Other combinations of garnets and III-V compounds will be apparent to those skilled in the art.

In addition to the injection laser described above and shown in FIG. 1, optically pumped lasers may be formed from the materials shown in Table I. The garnets are transparent and lossless at wavelengths considered. The indices of refraction differ considerably (n = 1.8 or 1.9 for the garnets, and n > 3.2 for the III-V compounds) so that excellent waveguides and lasers can be made.

In addition to the production of solid state lasers, the invention may be used for the production of light-emitting diodes of desired frequency, where the frequency of the light emitted depends on the chemical composition of the device and therefore on the lattice constant.

It is also possible to apply the invention to electrical devices other than those considered above, so that new combinations of compounds will be possible in the fabrication of transistors and other electronic devices.

TABLE I

Wavelengths of III-V Semiconductor Lasers with Lattice Constant Half that of a Garnet

III-V Ternary Compounds

Garnet Compound: Garnet Composition	Garnet Compound: Lattice Constant	III-V Semiconductor (Compounded for Half the Garnet Lattice Constant): Composition	Wavelength
LuAG	11.91Å	$Al_xIn_{1-x}As$	1.19μm
		InP_xAs_{1-x}	1.24
		$GaAs_xSb_{1-x}$	1.79
		$InGa_{1-x}As_x$	1.90
YAG	12Å	$Al_xIn_{1-x}As$	1.82μm
		InP_xAs_{1-x}	2
		$GaAs_xSb_{1-x}$	1.87
		$InGa_{1-x}As_x$	2.43
GGG	12.38Å	$InAs_xSb_{1-x}$	6.9μm

III-V Quarternary Compounds

Garnet Compound: Garnet Composition	Garnet Compound: Lattice Constant	III-V Semiconductor (Compounded for Half the Garnet Lattice Constant): Composition	Wavelength
LuAG	11.91Å	$(Al_xIn_{1-x})_yGa_{1-y}As$	1.19 - 1.90μm
		$Al_xIn_{1-x}P_yAs_{1-y}$	1.19 - 1.24
YAG	12Å	$(Al_xIn_{1-x})_yGa_{1-y}As$	1.82 - 2.43μm
		$Al_xIn_{1-x}P_yAs_{1-y}$	1.82 - 2
GGG	12.38Å	$(Al_xGa_{1-x})_yIn_{1-y}Sb$	1.16 - 1.29μm
		$Al_xIn_{1-x}As_ySb_{1-y}$	.79 - 3.44

CLAIMS

1. A device including a first crystalline layer (1,11) having a first lattice constant A_1 and a second crystalline layer (2,12) epitaxially formed on at least a portion of the first layer and having a second lattice constant A_2 characterised in that one of the two ratios A_1/A_2 and A_2/A_1 of the first and second lattice constants is substantially equal to an integer other than unity.

2. A device as claimed in claim 1 wherein at least one of the layers (2,12) is of a semiconductor material.

3. A device as claimed in claim 2 wherein the semiconductor is a compound comprising elements from groups III and V of the periodic table of elements.

4. A device as claimed in any of the preceding claims wherein at least one of the layers (1, 11) is of a garnet material.

5. A device as claimed in claim 4 as dependent on claim 3 wherein the garnet material is lutetium - aluminium - garnet, yttrium - aluminium - garnet or gadolinium - gallium - garnet and the semiconductor material is a substituted III - V compound having a lattice constant substantially equal to half the lattice constant of the garnet.

6. A device as claimed in any of the preceding claims comprising at least two optical devices (13,15) epitaxially grown respectively on the second layer and directly on the first layer.

7. A device as claimed in claim 6 wherein one of the devices (15) is a magneto-optical device.

8. A device as claimed in claim 6 or claim 7 wherein one of the devices (13) is an electro-optical device.

9. A device as claimed in claim 8 wherein the electro-optical device is a light-emitting device.

10. A device as claimed in claim 9 wherein the light-emitting device is a solid-state laser.

11. A method of selecting crystalline substances for compatible epitaxial growth in which a first crystalline substance for forming a first crystalline layer has a first lattice constant A_1 and a second crystalline substance for forming a second crystalline epitaxial layer has a second lattice constant A_2 characterised in that one of the two ratios A_1/A_2 and A_2/A_1 of the first and second lattice constants is substantially equal to an integer other than unity.

FIG. 1

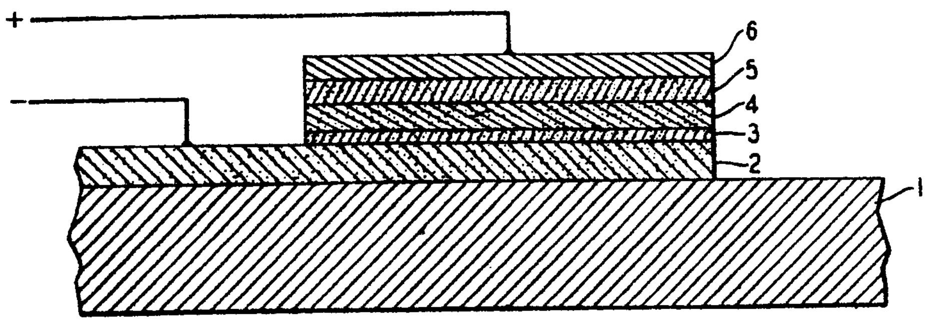

FIG. 2

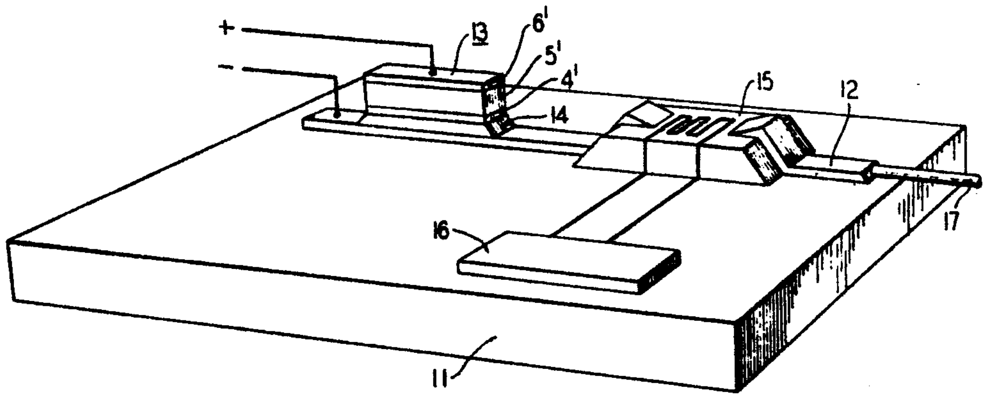

FIG. 2A

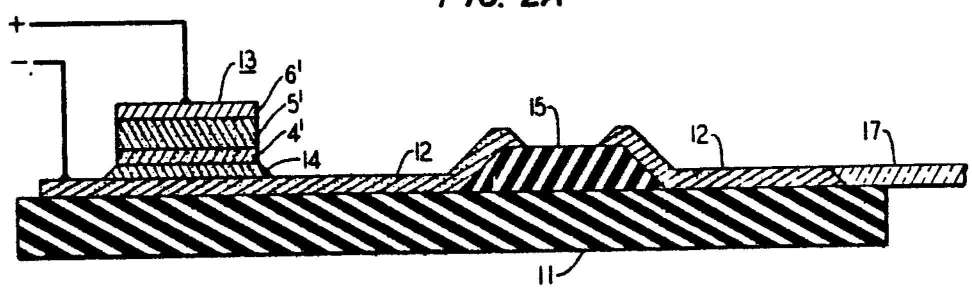

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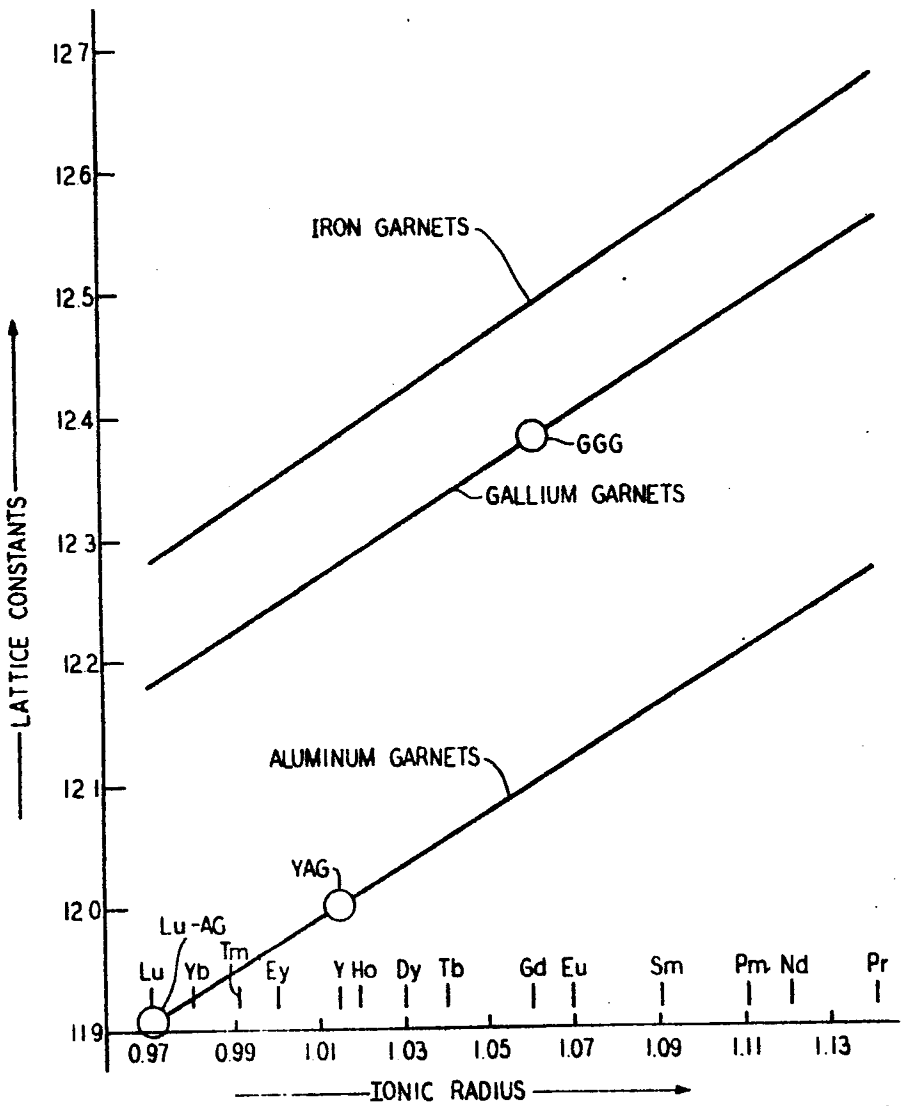
FIG. 3



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EUROPEAN SEARCH REPORT

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DOCUMENTS CONSIDERED TO BE RELEVANT			CLASSIFICATION OF THE APPLICATION (Int. Cl.²)
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	
A	BE - A - 751 978 (NORTH AMERICA ROCKWELL CORP.) * Page 1, paragraph 1 - page 2, paragraph 2; page 17, table; claims 1-4,8-10,21,22 *	1,11	
A	DE - A - 2 454 183 (A.GOETZBERGER) * Patentansprüche 1-2 *	11	
			TECHNICAL FIELDS SEARCHED (Int. Cl.²)

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DOCUMENTS CONSIDERED TO BE RELEVANT			CLASSIFICATION OF THE APPLICATION (Int. Cl.²)
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	
	IBM TECHNICAL DISCLOSURE BULLETIN, vol. 15, nr. 1, june 1972, New York, USA, E.A.GIESS et al."Growth of single crystal $MgGa_2O_4$ Spinel", pages 151-152 * Page 151, paragraph 1 *	1-3	H 01 L 29/04 H 01 L 27/15 H 01 L 21/208 G 02 F 1/09
	FR - A - 2 280 166 (SIEMENS) * Claims 1-3; figure 1 *	1,5-10	
			TECHNICAL FIELDS SEARCHED (Int.Cl.²)
A	IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-23, nr. 1, january 1975, New York USA, J.WARNER "Nonreciprocal magneto-optic waveguides", pages 70-78 * Figure 4 *	6-8	H 01 L 29/04 H 01 L 27/15 H 01 L 21/208 H 01 L 21/205 G 02 F 1/09 B 01 J 17/20 B 01 J 17/28
A	APPLIED PHYSICS LETTERS, vol. 21, nr. 5, 1 September 1972, New York, USA P.K.THIEN et al. "Optical wave-guides of single-crystal garnet films", pages 207-209 * Page 207, abstract; page 207, column 1, paragraph 1 *	1,6	CATEGORY OF CITED DOCUMENTS
A	US - A - 3 922 703 (RCA) * Claims 1-3; figures 1,2 *	6	X: particularly relevant A: technological background O: non-written disclosure P: intermediate document T: theory or principle underlying the invention E: conflicting application D: document cited in the application L: citation for other reasons
	./.		
X	The present search report has been drawn up for all claims		&: member of the same patent family, corresponding document

Place of search	Date of completion of the search	Examiner
The Hague	05-10-1978	VANCRAEYNEST

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