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(54) **WAVELENGTH DEMULTIPLEXING STACK PHOTODIODE DETECTOR WITH ELECTRICAL ISOLATION LAYERS**

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(52) **U.S. Cl.** **359/124**; 359/138

(58) **Field of Search** 359/124, 189, 359/193, 195; 250/339.01, 339.05; 257/440

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,627,383	*	5/1997	Cunningham	257/17
5,827,016	*	2/1999	Cunningham	437/107
5,949,561	*	9/1999	Gooossen	359/124

OTHER PUBLICATIONS

L. B. Aronson et al., "Low–Cost Multimode WDM for Local Area Networks," Conference on Optical Fiber Communications, *Technical Digest*, Postconference 6:420–3 (1997).

J. C. Campbell et al., "Improved Two–Wavelength Demultiplexing InGaAsP Photodetector," *IEEE Journal of Quantum Electronics*, QE–16, No. 6, pp. 601–603 (1980).

K. W. Goossen et al., "Electroabsorption in ultranarrow–barrier GaAs/AlGaAs multiple quantum well modulators," *Applied Physics Letters*, 64, No. 9, pp. 1071–1073 (1994).*

Swaminathan et al., "Material Aspects of GaAs and InP Based Structures," Crystal Growth, Ch. 2, pp. 138–155 (Prentice Hall, 1991).*

* cited by examiner

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(57) **ABSTRACT**

A wavelength demultiplexer having at least two pairs of photodetectors is disclosed. The photodetectors are arranged in sequential layers along an optical path and the pairs of photodetectors are separated by a non-optically active insulator interposed between the pairs. The photodetectors differ in bandgap, and are arranged so that the optical signal passes through relatively larger bandgap photodetectors before being received by relatively smaller bandgap detectors. Each photodetector absorbs photons within a predetermined energy range and generates a voltage as a function of the absorbed energy. The photodetectors can be used to detect, and hence demultiplex, a wavelength-division-multiplexed signal.

21 Claims, 4 Drawing Sheets

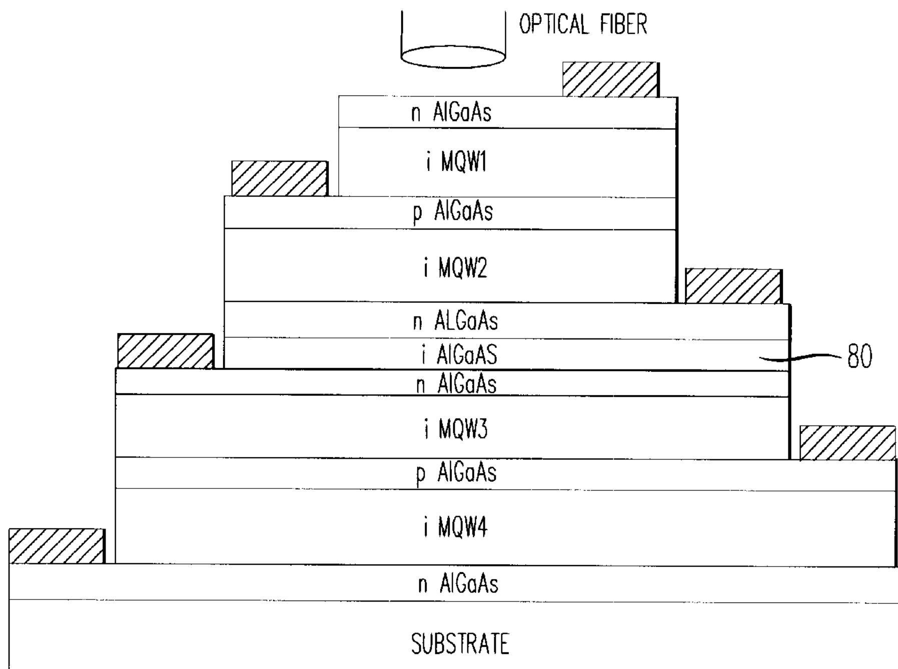


FIG. 1

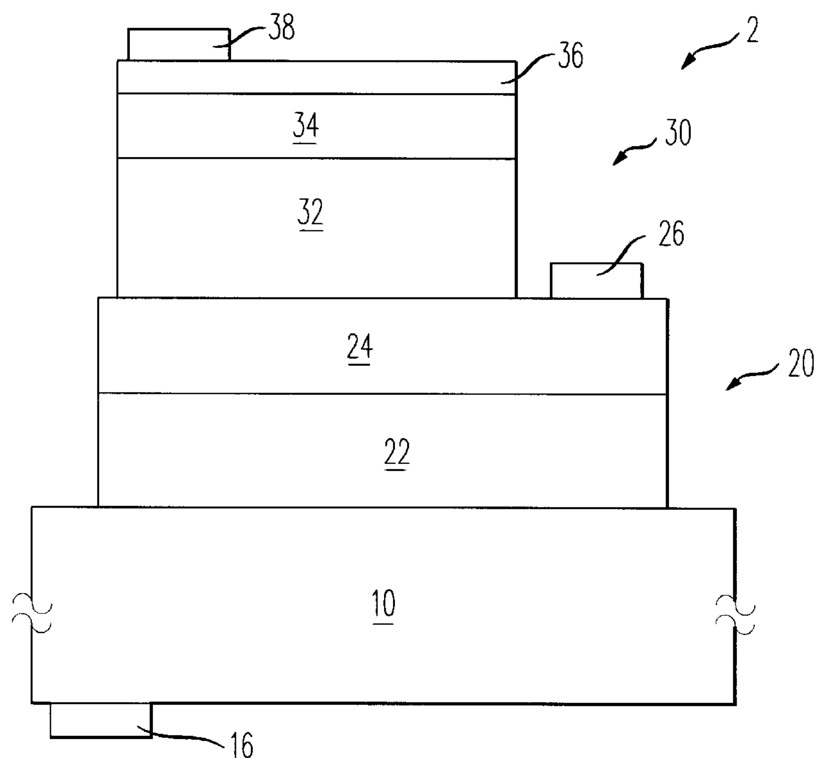


FIG. 2

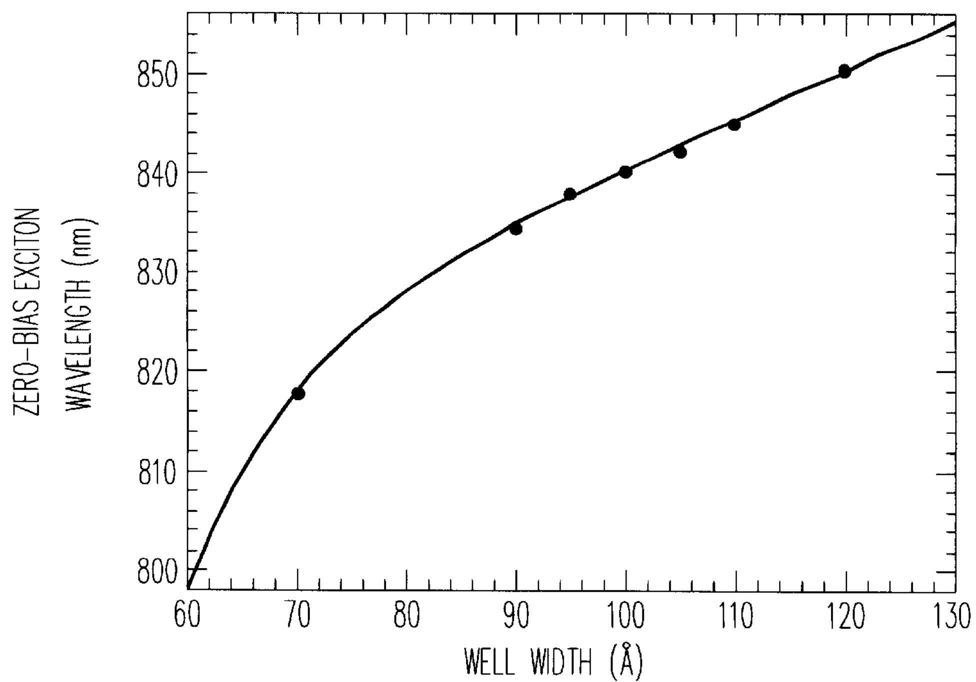


FIG. 3

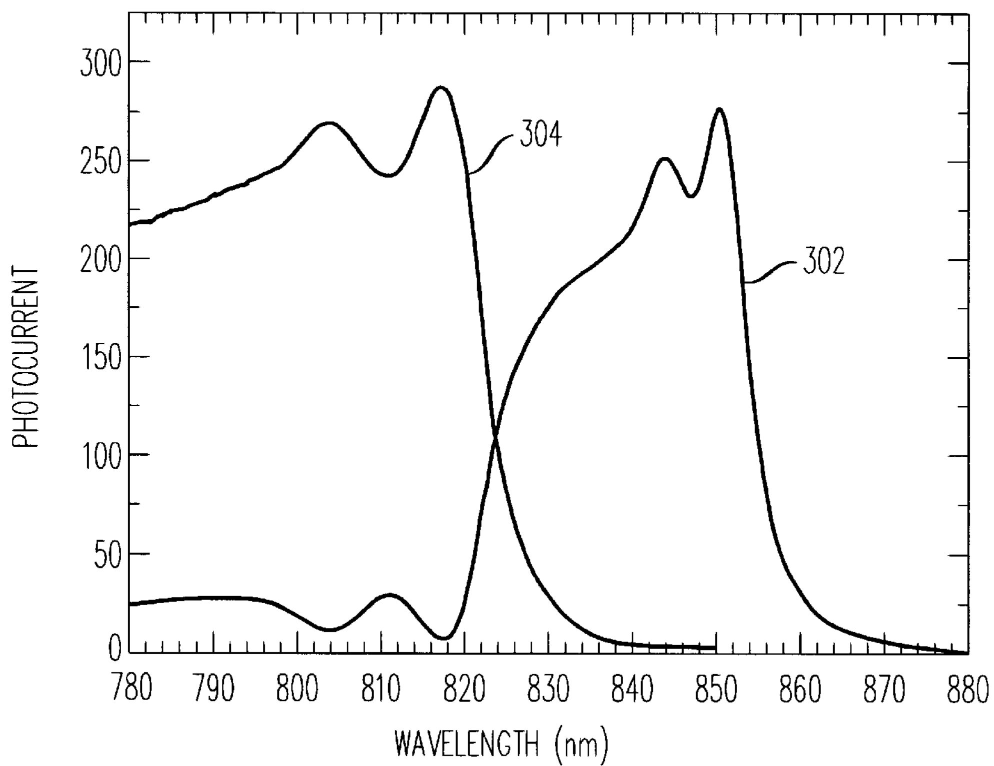


FIG. 4

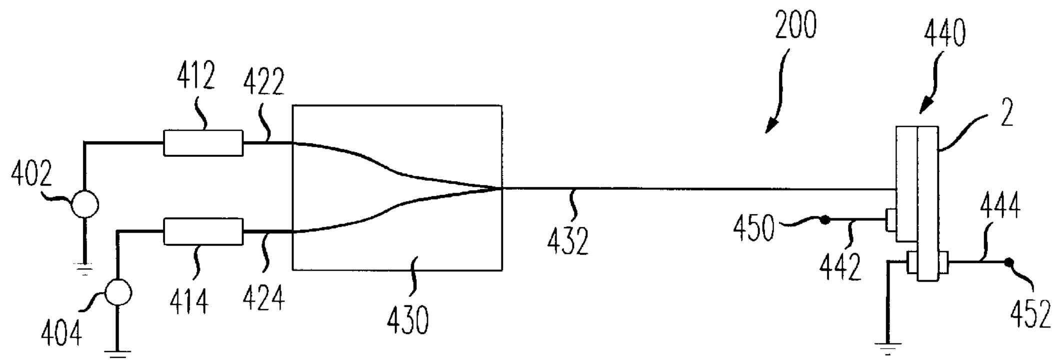


FIG. 5

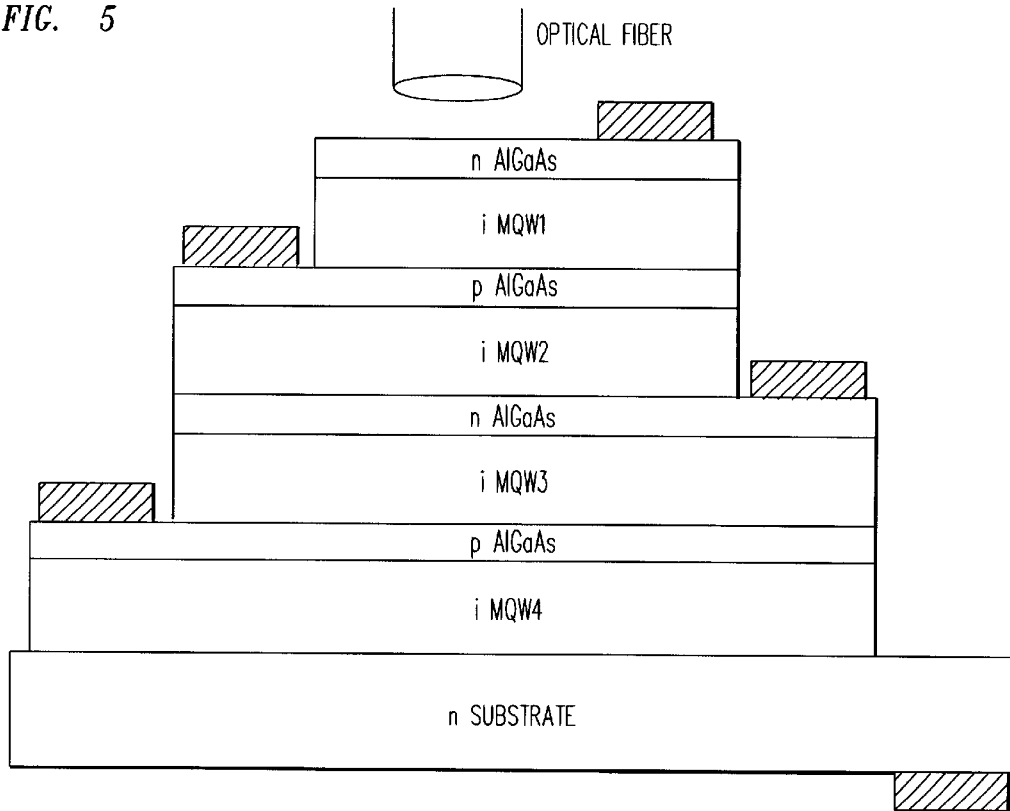


FIG. 6

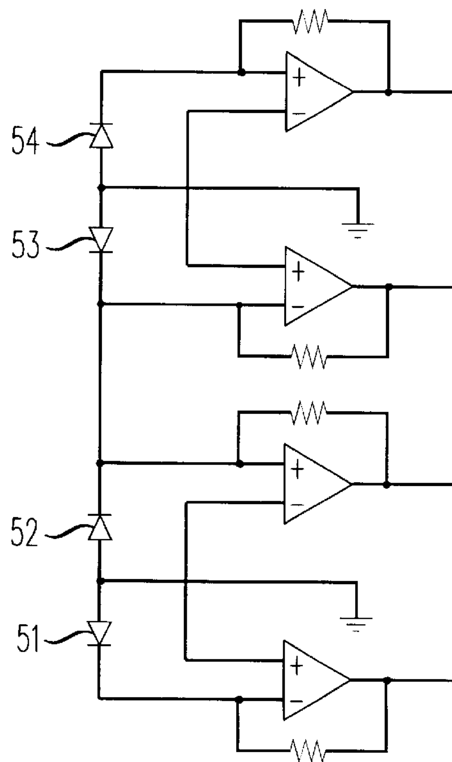


FIG. 7

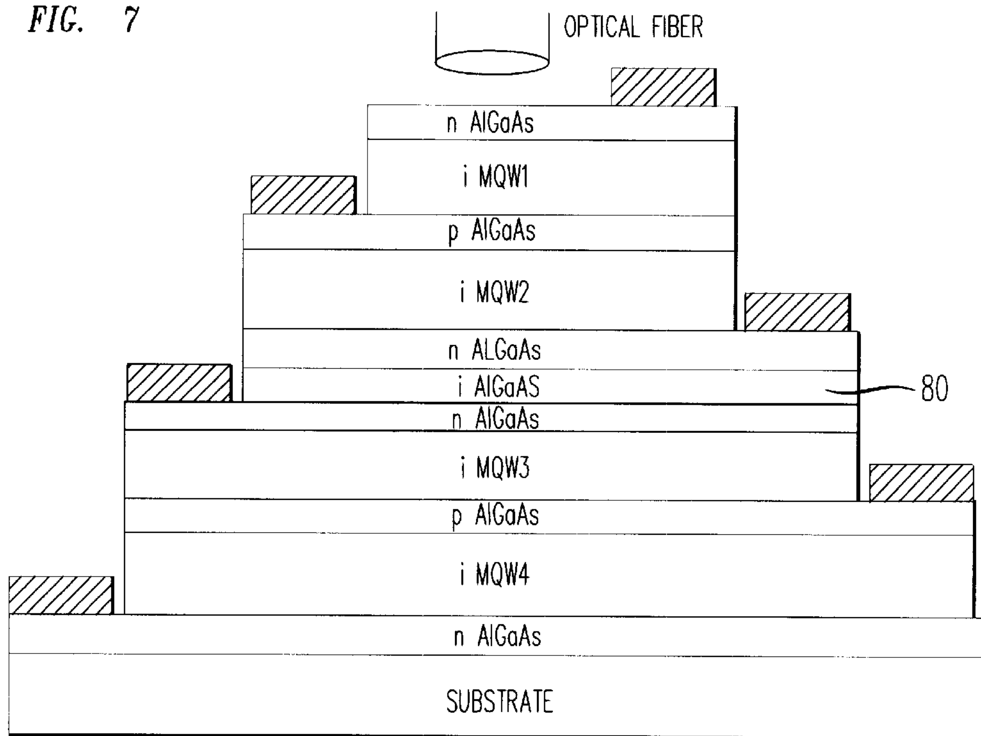
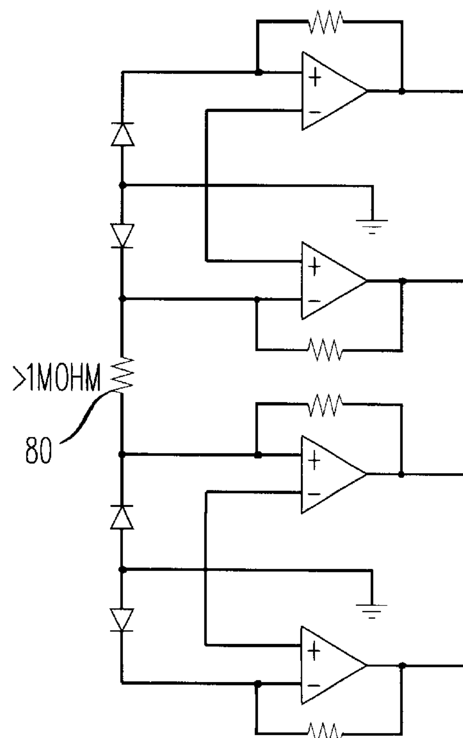


FIG. 8



WAVELENGTH DEMULTIPLEXING STACK PHOTODIODE DETECTOR WITH ELECTRICAL ISOLATION LAYERS

FIELD OF THE INVENTION

The present invention relates generally to optical communications devices and in particular to a device for demultiplexing optical signals.

BACKGROUND OF THE INVENTION

Optical communications may soon be the standard for high-speed local area networks (LAN). Within a few years, the data rates on such networks will be about one gigabit per second (Gbit/s). As capacity requirements exceed 1 Gbit/s, it may be desirable to use wavelength division multiplexing to increase the aggregate data rate of existing fiber in such LANs.

A multiple vertical cavity surface emitting laser (VCSEL) transmitter operating at 820, 835, 850 and 865 nm has recently been proposed as a WDM source for a LAN. To demultiplex the signal, a complicated arrangement of filters packaged with waveguide splitters was used. See, Aronson et al., "Low-Cost Multimode WDM for Local Area Networks," Postdeadline Session of the 1997 Optical Fiber Communication Conference.

It would be desirable, therefore, to have a simpler arrangement for demultiplexing such a signal to minimize the cost of such a network.

SUMMARY OF THE INVENTION

A wavelength demultiplexer having at least two pairs of "stacked" photodetectors is disclosed. The photodetectors are arranged in sequential layers along an optical path and the pairs of photodetectors are separated by a non-optically active insulator interposed between the pairs. The photodetectors differ in bandgap, and are arranged so that the optical signal passes through relatively larger bandgap photodetectors before being received by relatively smaller bandgap detectors. Each photodetector absorbs photons within a predetermined energy range and generates a voltage as a function of the absorbed energy. The photodetectors can be used to detect, and hence demultiplex, a wavelength-division-multiplexed signal.

In a preferred embodiment of the present invention, the photodetectors utilize multiple quantum well (MQW) material grown via molecular beam epitaxy. The MQW structure of the photodetectors enables the present photodetector-based demultiplexer to detect multiplexed signals that differ in wavelength by as little as 15 nanometers (nm). Conventional photodetector-based demultiplexers utilizing bulk materials cannot be used in conjunction with such close channel spacing. Typically, such conventional devices require channels separated by about 150 nm.

BRIEF DESCRIPTION OF THE DRAWING

Further features of the present invention will become more apparent from the following detailed description of specific embodiments thereof when read in conjunction with the accompanying drawing in which:

FIG. **1** shows an exemplary structure of a wavelength demultiplexing photodetector;

FIG. **2** shows a plot of heavy hole exciton wavelength versus well width;

FIG. **3** shows a photocurrent response spectra of a wavelength demultiplexing photodetector;

FIG. **4** shows the photodetector of FIG. 1 in use in a local area network;

FIG. **5** shows a preferred exemplary structure according to the present invention;

FIG. **6** shows a schematic of the structure of FIG. **5**;

FIG. **7** shows an alternative, preferred structure according to the present invention; and

FIG. **8**. shows a schematic of the structure of FIG. **7**.

DETAILED DESCRIPTION OF THE INVENTION

With reference now to FIG. **1**, there is shown an exemplary structure of a wavelength demultiplexing photodetectors (WDM-PD). Although this figure only shows an exemplary device having two photodiodes, those skilled in the art will quickly recognize that the device may be constructed with any number of such photodiodes depending upon the final application. More specifically, a preferred embodiment uses two pair of photodiodes (four photodiodes total).

Turning our attention back to FIG. **1**, a first photodiode **20** is grown on a III–V substrate **10**, such as indium phosphide (InP) or gallium arsenide (GaAs). A second photodiode **30** is grown on the first photodiode **20**. As will be appreciated by those skilled in the art, substrate selection is dependent upon optical signal wavelength, e.g., InP for long wavelength transmission (about 1300 nm) and GaAs for short wavelength transmission (about 780–850 nm).

The photodiodes comprising the WDM-PD are organized in the following manner. The upstream photodiode, i.e., the first photodiode to receive a wavelength-division-multiplexed signal, has the largest bandgap energy of all the photodiodes in the WDM-PD. Each subsequent photodiode has a smaller bandgap than the photodiode preceding it in the optical path. Upon contact with a photodiode, photons having energies at or above the bandgap of the photodiode are absorbed and lower energy photons are passed to the next photodiode. The process is repeated, with each photodiode absorbing photons having energies at or above that photodiode's bandgap energy. Smaller bandgap photodiodes are thereby filtered by the larger bandgap photodiodes so that all photodiodes receive a different range of wavelengths.

It should be appreciated from the foregoing that the specific structure of a WDM-PD is dependent upon the optical path taken through the WDM-PD. For example, if the substrate or support layer is opaque at the operating wavelengths of the WDM-PD, the wavelength-divisionmultiplexed signal should enter the device from the "top," so that a photodiode disposed on the substrate is the last to receive the signal. As such, the photodiode disposed on the substrate will have the smallest bandgap energy. In other embodiments, it may be desirable for the wavelength-division-multiplexed signal to enter through the substrate, so that the photodiode disposed on the substrate receives the signal first. In such an embodiment, the photodiode disposed on the substrate has the largest bandgap energy.

With continuing reference to FIG. **1**, the first photodiode **20** comprises a multiple quantum well (MQW) stack **22** followed by a doped layer **24**. The photodiode **20** has the usual p-i-n structure with the substrate **10** as the "n-" layer, the MQW stack **22** being the "i-" (intrinsic) layer, and the doped layer **24** being the "p-" layer. Contacts **16** and **26** are disposed on the substrate **10** and the doped layer **24** to which wires are attached for electrical connection to processing electronics.

It will be appreciated by those skilled in the art that the substrate **10** shown in FIG. **1** is not an essential element of

the WDM-PD. In the embodiment of a WDM-PD shown in FIG. **1**, the substrate **10** functions as a support, as well as the n-layer. A n-layer deposited on glass or other type of mechanical support can suitably be used in place of a n-type substrate.

The MQW stack **22** is a periodic layered structure. The size of the stack, i.e., the number of layers, controls the overall energy absorption. In other words, the layers within the stack are repeated as necessary to achieve a desired amount of energy absorption. The most basic period of an MQW stack consists of a layer of low band gap material, called the well, followed by a layer of higher band gap material, called the barrier. Layer thickness is in the range of the quantum mechanical wavelength of an electron, i.e., about 100 angstroms. The MQW stack produces sharp absorption lines near the band gap, called excitons. Excitons produce an absorption spectrum characterized by very high absorption at the exciton and very low absorption at slightly larger wavelengths, but closely spaced with the exciton. Thus, the present WDM-PD utilizing MQW material can advantageously demultiplex closely spaced wavelength channels.

Moreover, in the present WDM-PD utilizing MQW material, the position (wavelength) of the exciton, which determines operating wavelength of the photodiode, is advantageously determined by well layer thickness, and to a lesser extent by barrier layer thickness. Decreasing well size increases the effective band gap of the MQW. By contrast, in a WDM-PD utilizing bulk materials, such as described by Campbell et al, "Improved Two-Wavelength Demultiplexing InGaAsP Photodetector," IEEE J. Quantum Elec., v. QE-16, no. 6, pp. 601–603, June 1980, chemical composition of the semiconductor layers comprising the photodetector must be altered to change band gap.

Those skilled in the art will appreciate that a variety of materials can be used for the well layers and the barrier layers of the MQW stack **22**. In a presently preferred embodiment, the MQW stack **22** employs GaAs well layers and aluminum-arsenide (AlAs) barrier layers. To the inventors' knowledge, such an arrangement advantageously results in the highest absorption and the sharpest excitonic features, thereby enabling the closest wavelength spacing. Barrier layer size is preferably less than about 25 angstroms. At such a size, a relatively high photocurrent collection efficiency is realized resulting in a high conversion of optical to electrical signal. See, Goossen et al., "Electroabsorption in Ultranarrow-Barrier GaAs/AlGaAs Multiple Quantum Well Modulators," Appl. Phys. Lett., v. 64(9), pp. 1071–1073, Feb. 28, 1994, incorporated by reference herein.

With simultaneous reference now to FIG. **2**, there is shown a plot showing (heavy hole) exciton wavelength versus well width. The information contained in FIG. **2** can be used to determine well width as a function of the channels of a WDM signal. For example, a WDM-PD suitable for demultiplexing a WDM signal comprising spectral components at 820, 835 and 850 nm would include at least three photodiodes having respective well widths of about 70, 90 and 119 angstroms. The plot shown in FIG. **2** can be represented algebraically by the following expression:

$$\text{exciton wavelength (nanometers)}=797+0.45L-(1.2\times10^{12})/L^6 \quad [1]$$

where: L equals well width (angstroms).

FIG. **2** is applicable to photodiodes based on MQW stacks having twenty angstrom AlAs barriers and GaAs wells. The curve would change for other barrier compositions, thicknesses, and other well compositions. Curves for such other MQW stacks can be generated experimentally by those skilled in the art.

The MQW stack **22** and the doped layer **24** can be grown using conventional molecular beam epitaxy using solid Group V and Group III sources. See, for example, Swaminathan and Macrander, *Material Aspects of GaAs and Inp Based Structures,* pp. 138–155, (Prentice Hall, 1991). It will be appreciated from the foregoing description that the MQW stacks have precise dimensions thereby requiring accurate monitoring of growth. Reflection High Energy Electron Diffraction (RHEED) can be used for that purpose. According to RHEED, an approximately 10 keV narrow electron beam is diffracted at an angle of about 1° off the crystalline semiconductor surface onto a phosphorescent screen. As crystal growth proceeds, at approximately one atomic layer per second, the intensity of the reflected electron beam spot on the phosphorescent screen varies sinusoidally through a maximum at completion of an atomic layer, then through a minimum at half-completion of the next layer, and finally at a maximum as a function of time (through a suitable photocell detector with associated electronics and a recorder). See, Swaminathan and Macrander at 149–155.

The elemental sources contained within the MBE chamber are all controlled to within 1° centigrade; the Group V to Group III beam flux ratio is about 20, the growth temperature is approximately 640° C. and the growth rate is about one micrometer per hour. The sample is rotated during growth.

A second photodiode **30** is grown on the first photodiode **20**. The polarity of the second photodiode **30** is flipped relative to the polarity of the first photodiode **20**. Adjacent photodiodes, such as the photodiodes **20** and **30**, preferably share a layer in common. For example, the doped layer **24** serves as the p-layer for the second photodiode **30**, as well as for the first photodiode **20**. The intrinsic layer is again a MQW stack **32**. A n-layer **34** is disposed on the MQW stack **32**. Thus, the exemplary WDM-PD shown in FIG. **1** is arranged n-i-p-i-n. If additional photodiodes are present, the pattern of alternating polarity is continued.

If the uppermost photodiode layer tends to oxidize if unprotected, such as, for example, if such layer is comprised of AlGaAs, a cap layer can be disposed thereon. For example, in FIG. **1**, cap layer **36** is disposed on the layer **34**. A contact **38** is disposed on the cap layer **36** for connection to processing electronics. It should be appreciated that a set of contacts, one of which is preferably shared, is provided for each photodiode in the WDM-PD.

EXAMPLE

A WDM-PD was fabricated. The device included a n-type GaAs substrate, followed by two photodiodes. The photodiode grown on the substrate ("the bottom photodiode) consisted of a MQW stack comprising 75 periods of 120/20 Å GaAs/AlAs followed by a p^+ contact layer comprising 8000 Å $Al_{0.11}Ga_{0.89}As$. A second photodiode (the top photodiode) having a 200 period MQW stack comprising 70/20 Å GaAs/AlAs followed by a 2000 Å $Al_{0.11}Ga_{0.89}As$ n layer was grown on the first photodiode. The second photodiode was capped with a 100 Å GaAs n+ layer.

A photocurrent spectra of the WDM-PD is shown in FIG. **3**. The WDM-PD was illuminated on the surface of cap above the top photodiode. The spectra of the bottom photodiode is identified by the reference numeral **302** and the top photodiode is identified by the reference numeral **304**. The spectra was taken at zero bias on the photodiodes.

The MQW stack of the bottom photodiode has a heavy-hole absorption peak at 851 nm, and is low pass filtered by

the MQW stack of the top photodiode, which has a heavy-hole absorption peak at 818 nm. For two signals at 818 nm and 833 nm, there is less than −11 dB optical crosstalk between the two photodiodes. The optical crosstalk decreases to −16 dB for two signals at 818 nm and 838 nm.

Due to the quantum-confined Stark effect, if bias is applied, the MQWs absorption edges will red shift. If bias is desired for speed, such red shifting must be considered in MQW design.

FIG. **4** shows the exemplary WDM-PD of FIG. **1** in use in a local area network (LAN) **200**. The LAN **200** includes two single frequency optical sources, **412** and **414**, such as lasers, which are excited by drivers **402** and **404**. The optical signals **422** and **424** generated by respective sources **412** and **414** are multiplexed using a suitably configured multiplexer **430**, such as a Dragone router or the like. The drivers, optical sources and multiplexer can all be sited in the same location.

A wavelength-division-multiplexed signal **432** leaving the multiplexer is routed to a node **440** wherein a WDM-PD demultiplexes the signal. The WDM-PD generates and routes a first electrical signal **442** corresponding to the spectral component **422** to a first destination **450** and generates and routes a second electrical signal **444** corresponding to the spectral component **424** to a second destination **452**.

For ease of explanation, the LAN **200** is shown supporting a wavelength-divisionmultiplexed signal having two channels, i.e., spectral components. It will be appreciated that a signal possessing more than two channels can be suitably supported by appropriately increasing the number of optical sources and the number of photodiodes in the WDM-PD.

Turning our attention now to FIG. **5**, there is shown an exemplary WDM PD incorporating the previously described principles. Specifically, the device shown in FIG. **5** has four stacked photodiodes sequentially arranged in an optical path. As with the WDM PD device shown previously, the photodiodes that comprise this device are oriented such that an upstream photodiode has its polarity "flipped" relative to adjacent downstream photodiodes and that successive photodiodes along the optical path have different band gaps such that upstream photodiodes "filter" downstream photodiodes thereby resulting in each photodiode detecting a different range of wavelengths. As can be readily appreciated, the structure for this device is n-i-p-i-n-i-p-i-n as one proceeds from the bottom (substrate) to the top (optical fiber).

With reference now to FIG. **6**, there it shows in schematic form the configuration of FIG. **5** as part of a receiver circuit connected to a readout device, i.e., LCD or LED. As is shown in the figure, the configuration of FIG. **5** requires that the ground of an associated receiver circuit be connected to the signal line of the next receiver along the stack. While this configuration, using high-impedance amplifiers, provides for independent direct current (DC) photocurrent paths for each photodiode, there may be excessive AC crosstalk. This situation has been found correctable by introducing an insulating layer between every pair of photodiodes.

Specifically, and with reference now to FIG. **7**, there is shown a structure similar to that of FIG. **5**, with the further addition of an insulating layer disposed between the pairs of photodiodes. As shown, the structure of the improved device is now n-i-p-i-n-i (not photosensitive)-n-i-p-i-n. The schematic of this improved device is shown in FIG. **8**. Advantageously, the addition of insulating layer **80** allows for the addition of a single electrical contact while permitting the independent grounding of receiver circuits.

Although specific embodiments of the present invention have been described herein, it is to be understood that such embodiments are merely illustrative of the many possible specific arrangements that can be devised in application of the principles of the invention. Numerous and varied other arrangements can be devised in accordance with these principles by those of ordinary skill in the art without departing from the scope and spirit of the present invention.

The invention claimed is:

1. A wavelength demultiplexer comprising:

at least two pairs of photodetectors positioned along an optical path wherein the photodetectors differ in bandgap from one another and are arranged so that an optical signal passes through larger bandgap photodetectors before passing through smaller bandgap photodetectors and that each pair of photodetectors is separated by a non-optically active insulator such that the demultiplexer distinguishes channels separated by less than 150 nm.

2. The wavelength demultiplexer according to claim **1** wherein each photodetector includes:

a photodiode having a multiple quantum well stack suitable for absorbing a particular spectral component of a wavelength-division-multiplexed signal.

3. The wavelength demultiplexer according to claim **2** wherein each photodiode is characterized by a respective bandgap and are sequentially arranged within the demultiplexer such that the photodiode which is first to receive the wavelength-division-multiplexed signal has a larger bandgap than successive photodiodes which receive the wavelength-division-multiplexed signal.

4. The wavelength demultiplexer according to claim **3** wherein each successive photodiode to receive the wavelength-division-multiplexed signal has a smaller bandgap than any preceding photodiodes that received the wavelength-division-multiplexed signal.

5. The wavelength demultiplexer according to claim **4** wherein each multiple quantum well stack has a periodic structure, the period characterized by a barrier layer having a thickness less than about 25 angstroms and a well layer.

6. The wavelength demultiplexer according to claim **5** wherein each barrier layer consists substantially of aluminum arsenide.

7. The wavelength demultiplexer according to claim **6** wherein each well layer consists substantially of gallium arsenide.

8. The wavelength demultiplexer according to claim **4** further comprising:

a cap-layer, overlying a topmost photodiode.

9. A wavelength demultiplexer operable to demultiplex a wavelength-division-multiplexed signal, comprising:

a first photodiode pair including:

a first photodiode having a first multiple quantum well stack suitable for absorbing a first spectral component of the wavelength-division-multiplexed signal;

a second photodiode having a second multiple quantum well stack suitable for absorbing a second spectral component wavelength-division-multiplexed signal; and

a non-optically active insulator interposed between said first and second photodiode wherein the first and second photodiodes are characterized by respective first and second bandgaps, and are sequenced so that the photodiode which is first to receive the wavelength-division-multiplexed signal has a larger bandgap than the other photodiode; and

a second photodiode pair including:

a third photodiode having a first multiple quantum well stack suitable for absorbing a third spectral component of the wavelength-division-multiplexed signal;

a fourth photodiode having a second multiple quantum well stack suitable for absorbing a fourth spectral component of the wavelength-division-multiplexed signal; and

a non-optically active insulator interposed between the third and fourth photodiode, wherein the third and fourth photodiodes are characterized by respective first and second bandgaps, and are sequenced so that the photodiode which is first to receive the wavelength-division-multiplexed signal has a larger bandgap than the other photodiode; and

a non-optically active insulator interposed between the first and second pair of photodiodes;

such that the demultiplexer distinguishes channels separated by less than 150 nm.

10. The wavelength demultiplexer of claim **9** wherein each multiple quantum well stack has a periodic structure, the period characterized by a barrier layer having a thickness less than about 25 angstroms and a well layer.

11. The wavelength demultiplexer of claim **10** wherein the barrier layers are formed of aluminum arsenide.

12. The wavelength demultiplexer of claim **11** wherein the well layers are formed of gallium arsenide.

13. The wavelength demultiplexer of claim **9**, wherein the first photodiode is disposed on a support, the second photodiode is disposed on the first photodiode.

14. The wavelength demultiplexer of claim **13**, and further wherein the first photodiode comprises a first n-layer disposed on the support, a first i-layer disposed on the n-layer, and a first p-layer disposed on the first i-layer, and the second photodiode comprises the first p-layer, a second i-layer disposed on the first p-layer, and a second n-layer disposed on the second i-layer.

15. The wavelength demultiplexer of claim **14** wherein a cap layer is disposed on the fourth photodiode.

16. The wavelength demultiplexer of claim **14** wherein the first n-layer and the support are a n-type substrate.

17. The wavelength demultiplexer of claim **16** wherein the substrate is a Group III–V compound semiconductor.

18. The wavelength demultiplexer of claim **17** wherein the barrier layers are formed of aluminum arsenide, the well layers are formed of gallium arsenide, the first p-layer and the second n-layer are aluminum gallium arsenide.

19. The wavelength demultiplexer of claim **18** wherein a cap layer is disposed on a top surface of the demultiplexer such that oxidation of the top surface is minimized.

20. The wavelength demultiplexer of claim **10** wherein the well layers each have a width preselected to obtain the first and the second bandgaps, respectively.

21. The wavelength demultiplexer according to claim **20**, further comprising:

a first photodiode pair including:

a first photodiode having a first multiple quantum well stack suitable for absorbing a first spectral component of the wavelength-division-multiplexed signal;

a second photodiode having a second multiple quantum well stack suitable for absorbing a second spectral component wavelength-division-multiplexed signal; and

a non-optically active insulator interposed between said first and second photodiode, wherein

the first and second photodiodes are characterized by first and second bandgaps, and are sequenced so that the photodiode which is first to receive the wavelength-division-multiplexed signal has a larger bandgap than the other photodiode; and

a second photodiode pair including:

a third photodiode having a first multple quantum well stack suitable for absorbing a third spectral component of the wavelength-division-multiplexed signal;

a fourth photodiode having a second multiple quantum well stack suitable for absorbing a fourth spectral component of the wavelength-division-multiplexed signal; and

a non-optically active insulator interposed between the third and fourth photodiode, wherein

the third and fourth photodiodes are characterized by second bandgaps, and are sequenced so that the photodiode which is first to receive the wavelength-division-multiplexed signal has a larger bandgap than the other photodiode; and

a non-optically active insulator interposed between the first and second pair of photodiodes;

wherein each multiple quantum well stack has a periodic structure, the period characterized by a barrier layer having a thickness less than about 25 angstroms and a well layer;

wherein the well layers each have a width preselected to obtain the first and second bandgaps;

and further wherein the first and second widths are calculated using the expression:

$$SC=797+0.45L-(1.2\times10^{12})/L^6$$

where:

SC is the wavelength, in nanometers, of the spectral component to be absorbed;

L equals well width, in angstroms;

barrier layers are formed of aluminum arsenide and each have a width of 20 angstroms; and

the well layers are formed of gallium arsenide.

* * * * *