

Description

Field of the Invention

This invention relates to devices useful as sensors of magnetic fields as specified in the preamble of claim 1.

Background of the Invention

At present a wide variety of magnetic field sensors are already known. Of particular interest are magnetodiode sensors of the kind that employ a semi-conductive element into which are injected hole and electron charge carriers from opposite ends. The semi-conductive element is made non-homogeneous so that it includes at least two regions of very different recombination times for charge carriers therein. A magnetic field to be sensed is made to traverse the semi-conductive element in a specific direction. In that direction, the resulting Lorentz force deflects the charge carriers initially injected into one of the two regions into the other of the two regions. Such deflection results in a change of the amount of current flowing between the two ends of the semi-conductive element. The basic principles of magnetodiode sensors of this kind are described in a paper by Kataoka entitled "Recent Developments of Magnetoresistive Devices and Applications" in circular No. 182 of the Electromechanical Laboratory, Agency of Industrial Science and Technology, Tokyo, Japan, December 1974.

The present invention relates to a magnetodiode type of magnetic sensor that is well-adapted for use as a position sensor, particularly for automotive applications, although its application is not so limited.

In a magnetic field sensor of the kind described, sensitivity depends importantly on two parameters: (1) the mobilities of the charge carriers in the semi-conductive material forming the magnetodiode, and (2) the recombination time T_R . T_R is the average time it takes for a charge carrier of one sign to recombine with a charge carrier of the opposite sign after injection of the charge carrier into the semi-conductive material. Recombination occurs before the charge carrier reaches its charge collecting electrode. It is not known what specifically happens to the charge carriers when they recombine, but the result is a reduction in electrical current flow between complementary electrodes of the magnetodiode.

For high sensitivity to the effects of a magnetic field, the mobilities of the charge carrier should be high because the amount of deflection of the path of a charge carrier in the presence of a magnetic field normal to the path is proportional to the product of carrier mobility and magnetic field strength.

Also, for high sensitivity to the effects of a magnetic field, carrier recombination times should be long because the average distance a charge carrier can

travel in a semi-conductive material is proportional to the product of the recombination time and the drift velocity of the charge carrier.

In semi-conductive materials readily available for use in sensors of the kind described, a semi-conductive material such as silicon which is an indirect band-gap material, has a carrier recombination time that is attractively long. However, it has carrier mobilities that are relatively low. As indicated above, high mobilities are needed to obtain a magnetodiode having high sensitivity to a magnetic field. On the other hand, some compound semi-conductors, such as GaAs, InAs, $Bi_{1-x}Sb_x$, and InSb, which are direct band-gap materials, have carrier mobilities that are attractively high. However, their carrier recombination times are normally undesirably short. Because the recombination times are short, these materials have not been as sensitive as would be liked. The present invention represents a new approach to overcome the above shortcomings of the normally short carrier recombination times in such compounds, i.e., direct band-gap, semi-conductors. This approach involves using these latter materials to form distinctive diode structures that exhibit considerably longer carrier recombination times than conventional diode structures.

Summary of the Invention

A magnetic field sensor according to the present invention is characterised by the features specified in claim 1.

For use in a magnetic field sensor of the kind discussed, the invention includes a semi-conductive element that provides carriers of high mobility and long recombination times. To this end there is used a semi-conductive element that is formed of a direct band-gap material and that has a periodic doping profile through its thickness consisting of very thin alternate n- and p-doped layers, preferably with intrinsic zones therebetween, known variously as doping superlattices or n-i-p-i superlattices.

The properties of doping superlattices have been described in detail in papers by G. H. Dohler, entitled, "n-i-p-i Doping Superlattices-Metastable Semiconductors With Tunable Properties," Journal of Vacuum Science and Technology, B, Vol. 1, No. 2, April-June 1983, pps. 278-284, and "Physics and Applications of Doping Superlattices," a paper from pages 270-284 of the book Two-Dimensional Systems, Physics and New Devices: Proceedings of the International Winterschool, Mauternsdorf, Austria, 1986, published by Springer Verlag, Berlin 1986. As discussed therein, the unusual properties of doping superlattices derive from the different nature of the superlattice potential, which is the space charge potential of ionized impurities in the doping layers. The space charge potential in the doping superlattices modulates the band edges

of the host material and the electrons and holes become spatially separated. The separations can be controlled by appropriate choice of the doping concentrations and the layer thicknesses. It is this latter property that is most important to this invention. The degree of confinement of carriers within their respective layers is directly related to the band-gap of the semi-conductive materials forming those layers. The spatial separation of holes and electrons results in a partial compensation of the impurity space charge potential such that, with increasing carrier concentration, the amplitude of the doping superlattice potential decreases and the effective band-gap increases. Associated with this tunability; i.e., increase, of the band-gap is a tunability; i.e., increase, of the recombination time due to a reduction of the tunnelling or increase in thermal barriers for recombination. Such spatial separation in the superlattice dramatically lengthens recombination times of carriers over the time they exhibit in bulk materials; i.e., non-superlattice structures. However, mobilities are not effectively reduced. Recombination times in the superlattice are not just slightly increased, they are increased many orders of magnitude, over that of the bulk material. For example, lifetimes can be increased from 1-10 nanoseconds to one second or more. Moreover, large excess carrier concentrations in the layers can be achieved at relatively low injection currents as compared to bulk material of the same doping concentration.

It appears that hitherto doping superlattices have been proposed primarily for electro-optic devices with an electric field established normal to the layers for current flow normal to the layers. However, the first of the two cited Dohler papers also discusses the tuning of the carrier concentration in doping superlattices by the injection of carriers selectively into the various layers via electrodes. In particular, studies were mentioned in which there were provided two spaced-apart electrodes. The first spaced-apart electrode provides ohmic contacts to all the n-type layers for injection of electrons therein but blocking contacts to the p-type layers. The second spaced-apart electrode provides ohmic contacts to all the p-type layers for injection of holes therein but blocking contacts to all the n-type layers. Moreover, reference was made to magnetotransport experiments with the magnetic field parallel and perpendicular to the layers that established the two-dimensional character of the system. However, no magnetic device applications are suggested.

In a magnetic field sensor in accordance with the present invention, illustratively a magnetodiode, a doping superlattice having layers largely of long carrier recombination times is provided with injecting contacts at opposed surfaces for selective charge carrier injection, as just discussed, for carrier flow essentially parallel to the layers. The device is to oper-

ate under forward bias, that is, the p-type regions biased positively with respect to the n-type regions. Current carriers injected into one end of a given layer will travel varying lengths of that layer, pass through the p-n junction separating that layer from a contiguous layer, and then complete their travel to the other end of the second layer. Therefore, after travelling a trajectory inside one of the layers that is essentially parallel to the major faces of the layer, the carriers ultimately cross the p-n junctions that separate those layer major faces from major faces of contiguous layers. Once passing through the p-n junction, the carriers continue to travel in the second layer in a trajectory that is essentially parallel to the major faces of the second layer. A magnetic field to be sensed is applied in the direction perpendicular to the layers. This will deflect the charge carriers during their motion parallel to the layers in the transverse direction, normal to the magnetic field.

Additionally, each of the layers of the doping superlattice is provided with a region of short carrier recombination time, such that this transverse deflection of the charge carriers in each layer moves them into such a region for recombination. In a p-i-n diode, at a given voltage, increasing the rate of recombination reduces the effective current flow between its complementary electrodes. Accordingly, in a device according to the present invention, the magnetic field can be sensed as a reduction in the current flow between the injecting contacts in a manner analogous to conventional magnetodiodes.

Brief Description of the Drawing

Figure 1 schematically shows a plan view of an end of a semi-conductive element in the form of a doping superlattice comprising alternate n-type and p-type layers;

Figure 2 schematically shows a three-dimensional view of a magnetodiode sensor in accordance with an illustrative embodiment of the present invention, including a semi-conductive element of the kind shown in Figure 1; and

Figure 3A is a top view of another illustrative embodiment of the present invention including a pair of magnetodiodes useful in a differential sensor; and

Figure 3B is a cross-section taken along the lines BB of Figure 3A.

Detailed Description

With reference now to Figure 1, the semi-conductive element 11 is a doping monocrystalline superlattice structure comprising alternately of thin monocrystalline n-type layers 12 and lattice-matched thin monocrystalline p-type layers 14. It is common

practice in the art to describe such a structure as an n-i-p-i superlattice even in the absence of any intentionally undoped intermediate zones between the n-type and p-type layers. This is because the electrostatic bending of the energy bands associated with such layers will effectively induce intermediate zones having insignificant concentrations of free charge carriers, and so effectively of intrinsic conductivity type. Advantageously, layers 12 and 14 of element 11 are of a direct band-gap compound semi-conductor, such as gallium arsenide, indium arsenide, indium antimonide or a bismuth-antimony alloy. Such semi-conductive materials are known normally in bulk to have high carrier mobilities but short carrier recombination times.

In the structure of the present invention, each layer advantageously has a thickness less than the Debye length of charge carriers to be injected in the layer. Typically these layers will have a thickness of between 5 and 300 nanometres (50 and 3,000 Angstroms). For convenience of design and manufacture, it is preferable to make each layer substantially of the same thickness, although this is unnecessary. The average doping concentration in each layer advantageously is between 10^{16} and 10^{18} atoms per cubic centimetre. The thinner the layers, the higher the doping concentration should be to assure enough free carriers for good conductivity in each layer. The length of each layer should be less than the diffusion length of the current carrier in the layer. More specifically, it should be a length less than T_R times the drift velocity of the carrier. On the other hand, preferably it should be long enough for effective disposition of a short recombination time region between its ends. It should also be long enough for deflection of current carriers into the short recombination time region under the strength of the magnetic fields expected to be sensed. Typically this length will be between 10 micrometres and 500 micrometres. Advantageously there will be a total of between 10 and 100 such layers in element 11, depending on the amount of output current desired, although even as few as two layers may sometimes be enough.

Various known techniques are available for providing such layers in element 11, for example, molecular beam epitaxy (MBE), chemical vapor deposition (CVD) and metal-organic chemical vapor deposition (MOCVD). Typically, the various layers will have been grown epitaxially on a suitable high-resistivity monocrystalline substrate having a lattice constant as closely matching that of layers 12 and 14 as is obtainable, so that layers 12 and 14 will be substantially monocrystalline and provide high carrier mobility and recombination times.

For use in a magnetic sensor of the invention, it is essential to also provide in each of layers 12 and 14 a region in which the carriers have considerably shorter recombination times and into which the carriers

may be deflected by the magnetic field being sensed. As hereinbefore mentioned, the current carriers injected into a given layer travel essentially parallel to the major surfaces of that layer until they trickle through into the contiguous layer, or layers, where they then continue to travel essentially parallel to the layer major surfaces. This is how they get from one end of this device to the other.

A magnetic field normal to these layers will deflect the current carriers parallel to the layer major faces. In this invention, such a magnetic field will cause more current carriers to pass through the region of each layer having a much higher rate of recombination than when no magnetic field is present. A greater percentage of them will thus not be able to complete their draft through or parallel to the layers 12 and 14. The measured current flow between electrodes at the ends of these layers is thus modulated directly in accordance with the strength of the magnetic field being sensed. The regions of low recombination times in these layers are desirably formed on one surface of the element, as will be discussed in connection with Figure 2.

Figure 2 schematically shows a perspective view of a semi-conductive element 11 of the kind shown in Figure 1 used in a magnetodiode that is connected in a circuit that will measure the intensity of a magnetic flux B in a direction normal to the parallel n-type and p-type layers 12 and 14 of the element.

To this end, an n-type injecting electrode 18 is provided along one face of the element to contact one end of each of the layers 12 and 14, and a p-type injecting electrode 19 is provided along the opposite face of the element to contact the opposite end of each of the layers 12 and 14. A bias voltage is applied between the opposite ends of the layers 12 and 14 by a DC voltage source 20 connected between electrodes 18 and 19 of appropriate polarity so that the electrode 18 will inject electrons selectively into the n-type layers 12 and electrode 19 will inject holes selectively into the p-type layers 14. A resistor 22 is connected in series in this circuit and the voltage thereacross monitored as a measure of the current flowing in the circuit. Even though electrode 18 is forward-biased with respect to layers 14 and so will introduce electrons therein, and electrode 19 is forward-biased with respect to n-layers 12 and so will introduce holes therein, most of the current will flow between the n-type and p-type layers 12 and 14, respectively, for two basic reasons. First, the contact area between layers 12 and 14 is much larger than the total contact area between layers 12 and electrode 19 or layers 14 and electrode 18, respectively. Additionally, the contact electrodes 18 and 19 correspond to material which is much more heavily doped than layers 12 and 14, and this raises the contact potential between electrode 18 and layers 14 and electrode 19 and layers 12, respectively. A doping concentration greater than

about 10^{19} can be used in electrodes 18 and 19.

The injecting electrodes 18 and 19 can be readily formed simply by implanting appropriate ions to form heavily doped regions at opposite ends of the layers, in particular donor ions for electrode 18 and acceptor ions for electrode 19. The material is then generally thermally annealed to activate the implanted ions and to repair any damage caused by the implantation. It is also usual to provide metallic coatings over such electrodes to facilitate making low-resistance contact to such electrodes.

The entire front face 24 of the element as seen in Figure 2 is treated to be a region of short recombination times, denoted by the stippling. Injected electrons and holes drifting in their respective layers are deflected towards said face 24 by the Lorentz force resulting from the action of the magnetic field B. Various techniques are known for forming this face into a region of short recombination times. These techniques include inflicting damage on the crystalline structure of such surface by chemical etching, mechanical abrasion, and un-annealed ion implantation.

Proton bombardment, in the case of a gallium arsenide element, is known to convert gallium arsenide into an insulator-like; i.e., high resistivity material. Moreover, it forms an interface with the implanted gallium arsenide that retains the characteristic of providing relatively long recombination times. Accordingly, proton bombardment can be used, if desired, to treat the back surface 26, opposed to surface 24, to keep said back surface of a long recombination lifetime, while isolating the active portions of the layers (those shown) from the remaining portions of the layers (not shown) of the epitaxial film, or from the environment. In such instance, electrodes 18 and 19 should not extend past surface 26 onto the remaining epitaxial film. Alternatively, if the magnetic sensor is intended to be symmetrical with respect to the direction of the magnetic field B, the back surface 26 should be treated in the manner of front surface 24 so that holes and electrons deflected thereto by a magnetic field of the opposite direction will also readily recombine there.

A possible shortcoming with the design shown in Figure 2 is that, with some semi-conductors of possible interest, damaging the front surface 24 tends to break bonds between atoms in the surface layer and thereby tends to create a high density of low-mobility free carriers therein so that said surface 24 becomes conductive. Such a conductive surface can serve as an electrical short between contacts 18 and 19, diverting current that would otherwise pass through the bulk portion where the current is being monitored. This would reduce the sensitivity of the sensor. A possible solution to this problem is to include a damaged surface layer that is not continuous between the electrodes 18 and 19, as shown in Figures 3A and 3B.

Figures 3A and 3B show this solution in an em-

bodiment that also shows an integrated pair of magnetodiodes 30 and 40. Magnetodiodes 30 and 40 are electrically separated from one another by means of a V-shaped groove or trench 50. Each diode includes a doping superlattice essentially of the kind shown in Figure 1. Each diode may be viewed as a layered mesa on a semi-insulating substrate 52. Typically, the structure may be formed by epitaxially growing the desired number of layers on the semi-insulating substrate and thereafter forming the trench 50 to divide the layers into two separate sets of layers that form two separate diode layers. Each of the two sets of layers is provided at its opposite ends with its own discrete n-type electrode 32, 42, analogous to electrode 18 and a p-type electrode 34, 44, analogous to electrode 19.

A series of separate regions 54 of short carrier recombination times, as seen in Figure 3A, is provided along the walls of the trench 50. Typically, these can be formed by providing an appropriately apertured mask along the trench and then selectively damaging the unmasked regions (as by un-annealed ion implantation) to form the desired short recombination time regions 54. By keeping such regions 54 spaced apart, there is avoided the problem previously discussed of forming a shorting conductive layer. Moreover, as indicated by the stippling, the outer surfaces 35 and 45 of diodes 30 and 40, respectively, may be treated to be surfaces of relatively long recombination times, in the manner previously discussed for the back surface 26 in the embodiment of Figure 2.

Because regions 54 are separate, it is feasible to use a wider variety of techniques for shortening the carrier recombination times therein, such as providing ohmic contacts, typically by the deposition of metals suitable for that purpose. In the case of gallium arsenide, suitable metals include AuGeNi alloys, indium and platinum. In such instances, the structure is heated during or after metal deposition to melt the metal to form damaged surface regions with very short carrier recombination times.

It can be appreciated that the two diodes 30 and 40 will operate in opposite senses since an applied magnetic field of a direction to deflect the carriers in diode 30 towards the trench 50 will in diode 40 deflect such carriers towards the outer edge 45 of high recombination times rather than towards the trench 50. Conversely, an applied magnetic field of a direction to deflect the carriers in diode 40 towards the trench 50 will result in diode 30 in a deflection of such carriers towards its outer edge 35 of high recombination times. Such a pair of magnetodiodes is especially useful in differential sensors where the two magnetodiodes are supplemented by two additional fixed resistors to form the four branches of a conventional resistance bridge. Such differential arrangements are able to provide sensors with improved tolerance to temperature and power supply variations.

Firstly, while the invention will be of particular interest with use of direct band-gap materials where the improvement in recombination items will be greatest, it is also of interest with indirect gap materials such as silicon and germanium. Such materials in certain applications may be preferred for other reasons, such as lower cost or greater compatibility with other parts of the system in which the sensors are to be used.

Also, the long recombination times contemplated in the foregoing discussion are of the order of at least about 1 microsecond, generally about 100 microseconds to 1 second, and more. The short recombination times contemplated herein, as for example to be used in regions 24 and 54, are of the order of about 1-100 nanoseconds. As for mobility, by a reference to high mobility is meant a mobility of about 8,000 - 80,000 $\text{cm}^2\text{volt}^{-1}\text{sec}^{-1}$. By low mobility is meant a mobility of the order of 500-1,500 $\text{cm}^2\text{volts}^{-1}\text{sec}^{-1}$ or less. While the inventors do not have considerable test data to support the following thought, they believe that the ratio of high-to-low recombination times in this invention should be at least 10:1 and preferably about 100:1 and higher. On the other hand, it is conceivable that in certain circumstances the advantages of this invention might be achieved with a recombination time ratio of only 5:1.

Additionally, various other techniques may be used for forming localized short recombination time regions or long recombination time regions. In the embodiments described the magnetic field being tested is used for deflecting carriers normally flowing in long recombination time regions into short recombination time regions in order to decrease the output current with the increased magnetic field in the appropriate direction. Alternatively, structures may be devised in which the carriers normally flow in short recombination time regions and the magnetic field to be sensed is made to divert such flow into long recombination time regions, whereby the output current increases with increasing magnetic field in the appropriate direction.

Moreover, a variety of other arrangements are feasible for the short and long carrier recombination time regions. Additionally, whilst the invention has been described with particular reference to magnetodiodes, the principles involved are also applicable to magnetoresistors and to magnetotransistors.

Claims

1. A magnetic field sensor comprising a semi-conductive crystalline element (11;52) which comprises a doping superlattice of a plurality of layers formed by an n-i-p-i superstructure of a semi-conductive material which displays, in bulk, a relatively short carrier recombination time but a high carrier mobility; injecting electrodes

(18,19;32,34,42,44) along respective opposed faces of the element (11;52) to contact respective opposite ends of each of the layers (12,14); and where each of the layers (12,14) contains at least one region (26;30,40) of long carrier recombination times adjacent at least one region (24;54) of short carrier recombination times so that carriers are deflected between the regions of short and long carrier recombination times by a magnetic field to be sensed.

2. A magnetic field sensor according to claim 1, in which the semi-conductive element (11;52) is formed from a direct band-gap semi-conductor material.

3. A magnetic field sensor according to claim 1, in which the superlattice includes at least two layers.

4. A magnetic field sensor according to claim 1, in which each layer has a thickness less than the Debye length of charge carriers in said layer.

5. A magnetic field sensor according to claim 2, in which the semi-conductive element (11;52) is gallium arsenide, the superlattice includes at least 10 layers and the thickness of each layer is less than the Debye length of charge carriers in said layer.

6. A magnetic field sensor according to claim 1, in which the injecting electrodes at opposite ends of the semiconductive element (11;52) are p-type and n-type injecting contacts (18,19;32,34,42,44) extending across the superlattice of layers for injecting carriers for straight flow in any given layer, before crossing a p/n junction separating that layer from a contiguous layer, in the absence of the magnetic field to be sensed, and for transverse deflection in said given layer, before crossing a p/n junction separating that layer from a contiguous layer, in the presence of the magnetic field to be sensed.

7. A magnetic field sensor according to claim 6, in which said regions (24;54) of short carrier recombination times are included along an edge surface of the semi-conductive element (11;52).

8. A magnetic field sensor according to claim 7, in which said regions (54) of short carrier recombination times are discontinuous regions.

9. A magnetic field sensor according to claim 1, in which the semi-conductive element (52) includes a trench (50) extending transversely through the layers along the length of the semi-conductive



Firstly, while the invention will be of particular interest with use of direct band-gap materials where the improvement in recombination items will be greatest, it is also of interest with indirect gap materials such as silicon and germanium. Such materials in certain applications may be preferred for other reasons, such as lower cost or greater compatibility with other parts of the system in which the sensors are to be used.

Also, the long recombination times contemplated in the foregoing discussion are of the order of at least about 1 microsecond, generally about 100 microseconds to 1 second, and more. The short recombination times contemplated herein, as for example to be used in regions 24 and 54, are of the order of about 1-100 nanoseconds. As for mobility, by a reference to high mobility is meant a mobility of about 8,000 - 80,000 $\text{cm}^2\text{volt}^{-1}\text{sec}^{-1}$. By low mobility is meant a mobility of the order of 500-1,500 $\text{cm}^2\text{volts}^{-1}\text{sec}^{-1}$ or less. While the inventors do not have considerable test data to support the following thought, they believe that the ratio of high-to-low recombination times in this invention should be at least 10:1 and preferably about 100:1 and higher. On the other hand, it is conceivable that in certain circumstances the advantages of this invention might be achieved with a recombination time ratio of only 5:1.

Additionally, various other techniques may be used for forming localized short recombination time regions or long recombination time regions. In the embodiments described the magnetic field being tested is used for deflecting carriers normally flowing in long recombination time regions into short recombination time regions in order to decrease the output current with the increased magnetic field in the appropriate direction. Alternatively, structures may be devised in which the carriers normally flow in short recombination time regions and the magnetic field to be sensed is made to divert such flow into long recombination time regions, whereby the output current increases with increasing magnetic field in the appropriate direction.

Moreover, a variety of other arrangements are feasible for the short and long carrier recombination time regions. Additionally, whilst the invention has been described with particular reference to magnetodiodes, the principles involved are also applicable to magnetoresistors and to magnetotransistors.

Claims

1. A magnetic field sensor comprising a semi-conductive crystalline element (11;52) which comprises a doping superlattice of a plurality of layers formed by an n-i-p-i superstructure of a semi-conductive material which displays, in bulk, a relatively short carrier recombination time but a high carrier mobility; injecting electrodes (18,19;32,34,42,44) along respective opposed faces of the element (11;52) to contact respective opposite ends of each of the layers (12,14); and where each of the layers (12,14) contains at least one region (26;30,40) of long carrier recombination times adjacent at least one region (24;54) of short carrier recombination times so that carriers are deflected between the regions of short and long carrier recombination times by a magnetic field to be sensed.
2. A magnetic field sensor according to claim 1, in which the semi-conductive element (11;52) is formed from a direct band-gap semi-conductor material.
3. A magnetic field sensor according to claim 1, in which the superlattice includes at least two layers.
4. A magnetic field sensor according to claim 1, in which each layer has a thickness less than the Debye length of charge carriers in said layer.
5. A magnetic field sensor according to claim 2, in which the semi-conductive element (11;52) is gallium arsenide, the superlattice includes at least 10 layers and the thickness of each layer is less than the Debye length of charge carriers in said layer.
6. A magnetic field sensor according to claim 1, in which the injecting electrodes at opposite ends of the semiconductive element (11;52) are p-type and n-type injecting contacts (18,19;32,34,42,44) extending across the superlattice of layers for injecting carriers for straight flow in any given layer, before crossing a p/n junction separating that layer from a contiguous layer, in the absence of the magnetic field to be sensed, and for transverse deflection in said given layer, before crossing a p/n junction separating that layer from a contiguous layer, in the presence of the magnetic field to be sensed.
7. A magnetic field sensor according to claim 6, in which said regions (24;54) of short carrier recombination times are included along an edge surface of the semi-conductive element (11;52).
8. A magnetic field sensor according to claim 7, in which said regions (54) of short carrier recombination times are discontinuous regions.
9. A magnetic field sensor according to claim 1, in which the semi-conductive element (52) includes a trench (50) extending transversely through the layers along the length of the semi-conductive



element (52) for forming a pair of separate superlattices (30,40).

10. A magnetic field sensor according to claim 9, in which the injecting electrodes are separate injecting contacts (32,34,42,44) included at opposite ends of each of the pair of superlattices (30,40) and discontinuous regions (54) of short carrier recombination times are disposed along the trench (50).

11. A magnetic field sensor according to claim 10, in which the surfaces of the superlattices opposite the walls of the trench are continuous semi-insulating regions (35,45) of long carrier recombination times.

12. A magnetic field sensor according to claim 5, in which the average concentration of dopants in each of the layers is between 10^{16} and 10^{18} atoms per cubic centimetre and the thickness of each layer is between 5 and 300 nanometres.

13. A magnetic field sensor according to claim 2, in which the semi-conductive element (11;52) is of a material chosen from the group consisting of gallium arsenide, indium arsenide, indium antimonide, and bismuth-antimony alloys.

14. A magnetic field sensor according to claim 1, in which the sensor comprises: said semi-conductive element (11) in the form of a doping superlattice of a plurality of planar parallel layers (12,14) alternately of opposite conductivity types; means for passing through said element (11) a magnetic flux (B) having a varying component normal to the plane of the layers (12,14); means (18,19,20) for flowing current through a portion of the element (11) parallel to the layers (12,14); and means (22) for detecting the current flowing through said portion for sensing the magnitude of said varying component of the magnetic flux (B).

15. A magnetic field sensor according to claim 14, in which: the semi-conductive element (11) is formed from a compound semi-conductor; the superlattice includes between 10 and 100 layers (12,14); each of the layers (12,14) has a thickness between 5 and 300 nanometres; and the average doping concentration in each layer (12,14) is between 10^{16} and 10^{18} atoms per cubic centimetre.

16. A magnetic field sensor according to claim 1, which is formed as a magnetodiode which comprises said semi-conductive element (11) having a doping superlattice formed from a plurality of

planar parallel layers (12,14), contiguous layers being of opposite conductivity types, each layer including said regions (24,26) of short and long carrier recombination times; an n-type injecting contact (18) and a p-type injecting contact (19) at opposite ends of said layers (12,14) in the element (11), each being in contact with all of the layers but in blocking contact with different alternate layers for passing current through the layers and p/n junctions between said layers, the regions of short and long recombination times being positioned along the length of said layers so that current flowing in one of the two regions is transversely deflected to the other of the two regions by a component of magnetic flux (B) passing through the element (11) normal to the layers (12,14).

17. A magnetodiode according to claim 16, in which the semi-conductive element (11) includes between 10 and 100 layers (12,14), each having a thickness between 5 and 300 nanometres, and having an average doping concentration between about 10^{16} and 10^{18} atoms per cubic centimetre.

18. A magnetodiode according to claim 17, in which the semi-conductive element (11) is formed from a compound semi-conductor taken from the group consisting of gallium arsenide, indium antimonide, indium arsenide and bismuth-antimony alloys.

Patentansprüche

1. Ein Magnetfeldsensor mit einem halbleitenden kristallinen Element (11; 52), welches ein Dotterungsübergitter aus einer Vielzahl von Schichten umfaßt, die durch eine n-i-p-i-Überrückbau eines halbleitenden Materials gebildet sind, welches im Volumen eine relativ kurze Trägerrekombinationszeit, aber eine hohe Trägermobilität aufweist; Injizierungs Elektroden (18, 19; 32, 34, 42, 44) längs jeweiligen gegenüberliegenden Flächen des Elementes (11; 52), um jeweilige entgegengesetzte Enden der Schichten (12, 14) zu kontaktieren; wobei jede der Schichten (12, 14) zumindest einen Bereich (26; 30, 40) mit langen Trägerrekombinationszeiten benachbart zumindest einem Bereich (24; 54) mit kurzen Trägerrekombinationszeiten enthält, so daß Träger zwischen den Bereichen mit kurzen und langen Trägerrekombinationszeiten durch ein zu erfassendes Magnetfeld abgelenkt werden.

2. Ein Magnetfeldsensor nach Anspruch 1, in welchem das halbleitende Element (11; 52) aus ei-



nem Halbleitermaterial mit direkter Bandlücke gebildet ist.

3. Ein Magnetfeldsensor nach Anspruch 1, in welchem das Übergitter zumindest zwei Schichten umfaßt.
4. Ein Magnetfeldsensor nach Anspruch 1, in welchem jede Schicht eine Dicke kleiner als die Debye-Länge der Ladungsträger in der Schicht aufweist.
5. Ein Magnetfeldsensor nach Anspruch 2, in welchem das halbleitende Element (11; 52) Galliumarsenid ist, das Übergitter zumindest 10 Schichten umfaßt und die Dicke von jeder Schicht kleiner als die Debye-Länge der Ladungsträger in der Schicht ist.
6. Ein Magnetfeldsensor nach Anspruch 1, in welchem die Injektionselektroden bei entgegengesetzten Enden des halbleitenden Elementes (11; 52) injizierende Kontakte (18, 19; 32, 34, 42, 44) des p-Typus und des n-Typus sind, die sich über das Übergitter aus Schichten zum Injizieren von Trägern erstrecken, und zwar für den geraden Fluß in irgendeiner gegebenen Schicht, bevor ein p/n-Übergang überquert wird, der diese Schicht von einer angrenzenden Schicht trennt, in der Abwesenheit des zu erfassenden Magnetfeldes, und für Querablenkung in der gegebenen Schicht, bevor ein p/n-Übergang, der diese Schicht von einer angrenzenden Schicht trennt, überquert wird, in der Gegenwart des zu erfassenden Magnetfeldes.
7. Ein Magnetfeldsensor nach Anspruch 6, in welchem die Bereiche (24; 54) mit kurzen Trägerrekombinationszeiten längs einer Kantenoberfläche des halbleitenden Elementes (11; 52) umfaßt sind.
8. Ein Magnetfeldsensor nach Anspruch 7, in welchem die Bereiche (54) mit kurzen Trägerrekombinationszeiten diskontinuierliche Bereiche sind.
9. Ein Magnetfeldsensor nach Anspruch 1, in welchem das halbleitende Element (52) einen Graben (50) umfaßt, der sich quer durch die Schichten längs der Länge des halbleitenden Elementes (52) zum Bilden eines Paares von getrennten Übergittern (30, 40) erstreckt.
10. Ein Magnetfeldsensor nach Anspruch 9, in welchem die injizierenden Elektroden getrennte injizierende Kontakte (32, 34, 42, 44) sind, die an entgegengesetzten Enden von jedem des Paares von Übergitter (30, 40) beinhaltet sind und

diskontinuierliche Bereiche (54) mit kurzen Trägerrekombinationszeiten längs des Grabens (50) angeordnet sind.

11. Ein Magnetfeldsensor nach Anspruch 10, in welchem die Oberflächen der Übergitter entgegengesetzt den Wänden des Grabens kontinuierliche halbisolierende Bereiche (35, 45) mit langen Trägerrekombinationszeiten sind.
12. Ein Magnetfeldsensor nach Anspruch 5, in welchem die Durchschnittskonzentration der Dotierungsmittel in jeder der Schichten zwischen 10^{16} und 10^{18} Atome pro Kubikzentimeter beträgt und die Dicke jeder Schicht zwischen 5 und 300 Nanometern beträgt.
13. Ein Magnetfeldsensor nach Anspruch 2, in welchem das halbleitende Element (11; 52) aus einem Material besteht, das aus der Gruppe ausgewählt wird, die aus Galliumarsenid, Indiumarsenid, Indiumantimonid und Wismuth-Antimon-Legierungen besteht.
14. Ein Magnetfeldsensor nach Anspruch 1, in welchem der Sensor umfaßt: das halbleitende Element (11) in der Form eines Dotierungsübergitters aus einer Vielzahl von planaren parallelen Schichten (12, 14) alternierend mit Leitfähigkeit entgegengesetzter Typen; einem Mittel zum Durchführen eines Magnetflusses (B) mit einer variierenden Komponente normal auf die Ebene der Schichten (12, 14) durch das Element (11); einem Mittel (18, 19, 20) zum Fließenlassen von Strom durch einen Teil des Elementes (11) parallel zu den Schichten (12, 14); und einem Mittel (22) zum Nachweisen des durch den Teil fließenden Stromes zum Erfassen der Größe der variierenden Komponente des Magnetflusses (B).
15. Ein Magnetfeldsensor nach Anspruch 14, in welchem: das halbleitende Element (11) aus einem Verbindungshalbleiter gebildet ist; das Übergitter zwischen 10 und 100 Schichten (12, 14) umfaßt; jede der Schichten (12, 14) eine Dicke zwischen 5 und 300 Nanometern aufweist; und die durchschnittliche Dotierungskonzentration in jeder Schicht (12, 14) zwischen 10^{16} und 10^{18} Atome pro Kubikzentimeter beträgt.
16. Ein Magnetfeldsensor nach Anspruch 1, welcher als eine Magnetodiode gebildet ist, welche umfaßt: das halbleitende Element (11) mit einem Dotierungsübergitter, das aus einer Vielzahl von planaren parallelen Schichten (12, 14) gebildet ist, wobei angrenzende Schichten Leitfähigkeit entgegengesetzter Typen aufweisen, jede Schicht die Bereiche (24, 26) mit kurzen und lan-



gen Trägerrekombinationszeiten umfaßt; einem injizierenden Kontakt (18) des n-Typus und einem injizierenden Kontakt (19) des p-Typus an entgegengesetzten Enden der Schichten (12, 14) in dem Element (11), wobei sich jeder in Kontakt mit allen der Schichten, aber in blockierendem Kontakt mit unterschiedlichen alternierenden Schichten zum Durchführen von Strom durch die Schichten und p/n-Übergänge zwischen den Schichten befindet, die Bereiche mit kurzen und langen Rekombinationszeiten längs der Länge der Schichten positioniert sind, so daß der in einen der zwei Bereiche fließende Strom quer zu dem anderen der zwei Bereiche durch eine Komponente des Magnetflusses (B), die durch das Element (11) normal zu den Schichten (12, 14) tritt, abgelenkt wird.

17. Eine Magnetodiode nach Anspruch 16, in welcher das halbleitende Element (11) zwischen 10 und 100 Schichten (12, 14) umfaßt, wobei jede eine Dicke zwischen 5 und 300 Nanometern aufweist und eine mittlere Dotierungskonzentration zwischen ungefähr 10^{16} und 10^{18} Atomen pro Kubikzentimeter aufweist.
18. Eine Magnetodiode nach Anspruch 17, in welcher das halbleitende Element (11) aus einem Verbindungshalbleiter gebildet ist, der aus der Gruppe genommen ist, die aus Galliumarsenid, Indiumantimonid, Indiumarsenid und Wismuth-Antimon-Legierungen besteht.

Revendications

1. Détecteur de champ magnétique comprenant un élément cristallin semiconducteur (11; 52) qui comporte un super-réseau de dopage d'une pluralité de couches formées par une superstructure n-i-p-i d'un matériau semiconducteur qui affiche, en masse, un temps de recombinaison des porteurs relativement court mais une mobilité élevée des porteurs; des électrodes d'injection (18, 19; 32, 34, 42, 44) le long des faces opposées respectives de l'élément (11; 52) pour être en contact avec les extrémités opposées respectives de chacune des couches (12, 14); et où chacune des couches (12, 14) contient au moins une région (26; 30, 40) de longs temps de recombinaison des porteurs de telle sorte que les porteurs sont déviés entre les régions de court et de long temps de recombinaison des porteurs par un champ magnétique à détecter.
2. Détecteur de champ magnétique selon la revendication 1, dans lequel l'élément semiconducteur (11; 52) est formé à partir d'un matériau semicon-

ducteur à bande interdite directe.

3. Détecteur de champ magnétique selon la revendication 1, dans lequel le super-réseau comporte au moins deux couches.
4. Détecteur de champ magnétique selon la revendication 1, dans lequel chaque couche a une épaisseur inférieure à la longueur de Debye des porteurs de charge dans ladite couche.
5. Détecteur de champ magnétique selon la revendication 2, dans lequel l'élément semiconducteur (11; 52) est de l'arséniure de gallium, le super-réseau comporte au moins 10 couches et l'épaisseur de chaque couche est inférieure à la longueur de Debye des porteurs de charge dans ladite couche.
6. Détecteur de champ magnétique selon la revendication 1, dans lequel les électrodes d'injection aux extrémités opposées de l'élément semiconducteur (11; 52) sont des contacts d'injection de type p et de type n (18, 19; 32, 34, 42, 44) s'étendant sur le super-réseau de couches pour injecter des porteurs qui s'écoulent de manière rectiligne dans toute couche donnée, avant de croiser une jonction p/n séparant cette couche d'une couche contiguë, en l'absence du champ magnétique à détecter, et pour une déviation transversale dans ladite couche donnée, avant de croiser une jonction p/n séparant cette couche d'une couche contiguë, en présence du champ magnétique à détecter.
7. Détecteur de champ magnétique selon la revendication 6, dans lequel lesdites régions (24; 54) de courts temps de recombinaison des porteurs sont incluses le long d'une surface latérale de l'élément semiconducteur (11; 52).
8. Détecteur de champ magnétique selon la revendication 7, dans lequel lesdites régions (54) de courts temps de recombinaison des porteurs sont des régions discontinues.
9. Détecteur de champ magnétique selon la revendication 1, dans lequel l'élément semiconducteur (52) comporte une tranchée (50) s'étendant transversalement aux couches le long de la longueur de l'élément semiconducteur (52) pour former une paire de super-réseaux séparés (30, 40).
10. Détecteur de champ magnétique selon la revendication 9, dans lequel les électrodes d'injection sont des contacts d'injection séparés (32, 34, 42, 44) inclus aux extrémités séparées de chacune des paires de super-réseaux (30, 40) et de ré-

glons discontinues (54) à courts temps de recombinaison et sont disposées le long de la tranchée (50).

11. Détecteur de champ magnétique selon la revendication 10, dans lequel les surfaces des super-réseaux opposées aux parois de la tranchée sont des régions semi-isolantes continues (35, 45) de longs temps de recombinaison des porteurs.

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12. Détecteur de champ magnétique selon la revendication 5, dans lequel la concentration moyenne de dopants dans chacune des couches est comprise entre 10^{16} et 10^{18} atomes par centimètre cube et l'épaisseur de chaque couche est comprise entre 5 et 300 nanomètres.

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13. Détecteur de champ magnétique selon la revendication 2, dans lequel l'élément semiconducteur (11; 52) est en un matériau choisi parmi le groupe consistant en arséniure de gallium, en arséniure d'indium, en antimoniure d'indium, et en alliages de bismuth-antimoine.

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14. Détecteur de champ magnétique selon la revendication 1, dans lequel le détecteur comporte: ledit élément semiconducteur (11) se présentant sous la forme d'un super-réseau de dopage d'une pluralité de couches planes parallèles (12, 14) de types de conductivité alternativement opposés; des moyens pour faire passer par ledit élément (11) un flux magnétique (B) ayant une composante variable normale au plan des couches (12, 14); des moyens (18, 19, 20) pour faire circuler un courant dans une partie de l'élément (11) parallèle aux couches (12, 14); et des moyens (22) pour détecter le courant circulant dans ladite partie afin de détecter l'amplitude de ladite composante variable du flux magnétique (B).

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15. Détecteur de champ magnétique selon la revendication 14, dans lequel: l'élément semiconducteur (11) est formé à partir d'un semiconducteur composé; le super-réseau comporte entre 10 et 100 couches (12, 14); chacune des couches (12, 14) a une épaisseur comprise entre 5 et 300 nanomètres; et la concentration moyenne de dopage dans chaque couche (12, 14) est comprise entre 10^{16} et 10^{18} atomes par centimètre cube.

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16. Détecteur de champ magnétique selon la revendication 1, qui se présente sous la forme d'une magnétodiode qui comporte ledit élément semiconducteur (11) ayant un super-réseau de dopage formé à partir d'une pluralité de couches planes parallèles (12, 14), des couches contiguës étant de types de conductivité opposés, chaque couche comportant lesdites régions (24, 26) de

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courts et longs temps de recombinaison des porteurs; un contact d'injection de type n (18) et un contact d'injection de type p (19) aux extrémités opposées desdites couches (12, 14) dans l'élément (11), chacun étant en contact avec toutes les couches mais en contact de blocage avec différentes autres couches pour laisser passer le courant dans les couches et les jonctions p/n entre lesdites couches, les régions de courts et longs temps de recombinaison étant disposées le long de la longueur desdites couches de telle sorte que le courant circulant dans l'une des deux régions est dévié transversalement vers l'autre des deux régions par une composante de flux magnétique (B) passant par l'élément (11) normal aux couches (12, 14).

17. Magnétodiode selon la revendication 16, dans laquelle l'élément semiconducteur (11) comporte entre 10 et 100 couches (12, 14), ayant chacune une épaisseur comprise entre 5 et 300 nanomètres, et ayant une concentration moyenne de dopage comprise entre environ 10^{16} et 10^{18} atomes par centimètre cube.

18. Magnétodiode selon la revendication 17, dans laquelle l'élément semiconducteur (11) est formé à partir d'un semiconducteur composé pris dans le groupe consistant dans l'arséniure de gallium, l'antimoniure d'indium, l'arséniure d'indium et des alliages de bismuth-antimoine.

