Nov. 2, 1965 W. G. PFANN 3,215,568

SEMICONDUCTOR DEVICES

Filed Aug. 4, 1961

2 Sheets-Sheet 1

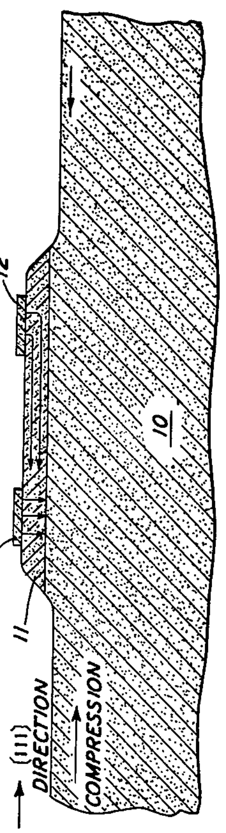

FIG. 3

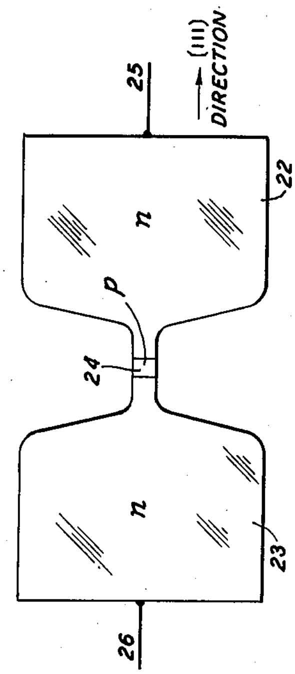

FIG. 4B

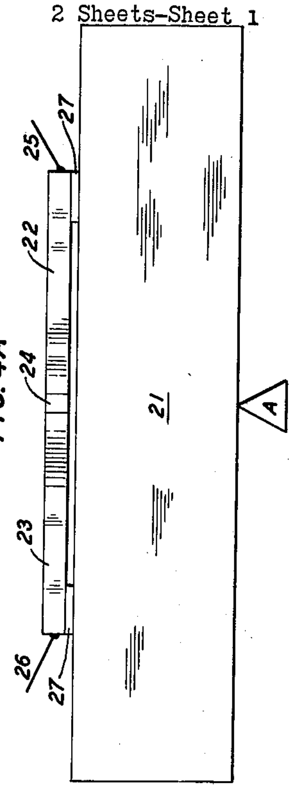

FIG. 4A

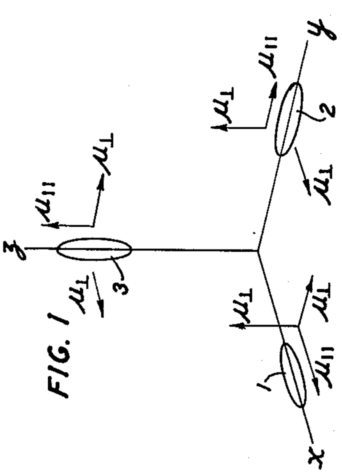

FIG. 1

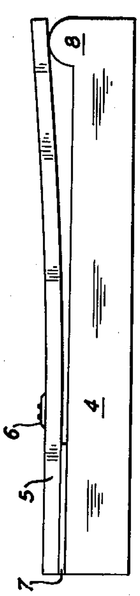

FIG. 2

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FIG. 5

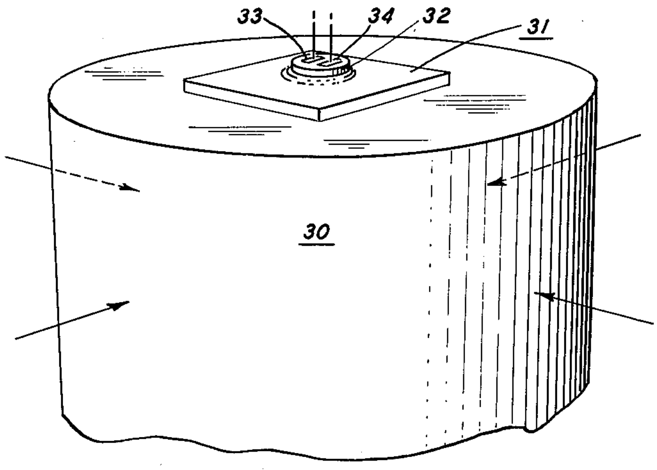
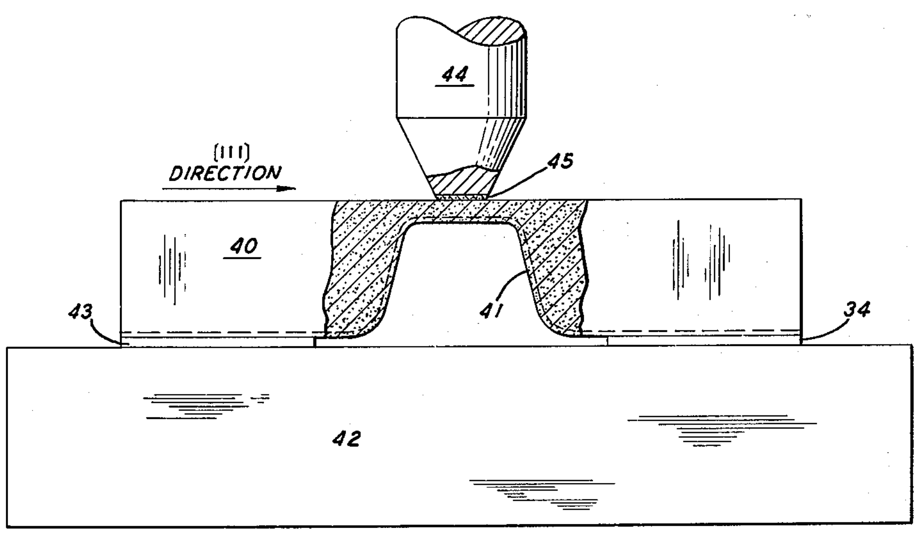


FIG. 6



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3,215,568
SEMICONDUCTOR DEVICES

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Filed Aug. 4, 1961, Ser. No. 130,458
14 Claims. (Cl. 148—33)

This application is a continuation-in-part of application Serial No. 43,494, filed July 18, 1960, now abandoned.

This invention relates to a procedure for improving semiconducting devices through the use of elastic strain. Further it concerns semiconducting devices in which the mobilities of holes and electrons are substantially varied through the use of directional strains which may be built into or otherwise provided for in the device during fabrication.

It has been found that the mobility of holes and electrons in various semiconducting materials can be increased or decreased by magnitudes of the order of 50% using elastic strains. These strains can be produced by either hydrostatic or directional pressures. The effect of hydrostatic pressure is primarily to vary the energy gap thus producing changes in diode resistivity responsive to pressure. This is disclosed with respect to particular diode constructions in United States Patent No. 3,065,636 issued November 27, 1962.

Directional pressures, however, have been found to additionally rely to a large degree on a different phenomenon involving strain responsive changes in electron or hole mobilities. This invention accordingly is directed to the use of directional strains in semiconductor devices to vary the carrier mobilities in certain prescribed manners and thereby enhance the performance of the device.

The advantages of increased or decreased mobilities of holes or electrons in various semiconducting materials and the device improvements made possible thereby are apparent to those skilled in the art. Heretofore the search for improved mobility characteristics has been confined entirely to a search for different kinds of semiconductors. This is because of the tacit assumption that the mobilities were isotropic, that is, for a given material the mobility is the same in all crystal directions. This was a natural assumption for those skilled in the art because the best known semiconductors all possess cubic symmetry, and hence, isotropic carrier mobilities.

In the present invention, however, the mobilities in certain critical directions in the devices are altered by directional elastic strains in such a manner as to improve the functioning of the devices. That is the mobilities are made anisotropic in materials normally exhibiting isotropic mobility. This invention also includes modifying the mobilities in materials having normally anisotropic mobility.

The variation of hole or electron mobilities with various directional strains can be explained by examining the attendant changes in distribution of electrons or holes in the various directional energy levels of the semiconductor crystal. This is known as the many-valley theory. The following discussion may be better understood when considered with the drawing in which:

FIG. 1 is a three dimensional diagram of the energy states of electrons in a semiconductor crystal;

FIG. 2 is a schematic front elevation view of an n-p-n mesa transistor fabricated with an inherent strain according to the principles of this invention;

FIG. 3 is a detailed sectional view of the mesa of FIG. 2 showing the directions of carrier flow and the mobilities incident thereto;

FIGS. 4A and 4B are top and front elevation views, respectively, of a different form of n-p-n transistor fabricated with inherent directional strain;

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FIG. 5 is a perspective view of a p-n-p mesa transistor appropriate for the application of the principles of this invention; and

FIG. 6 is a front elevation view partly in section of a varactor diode also having a construction which provides for inherent directional strain.

In FIG. 1, ellipsoids **1**, **2** and **3** are shown positioned on the *x*, *y*, and *z* axes, respectively, of an n-type semiconductor crystal such as silicon. The ellipsoids represent "valleys" and the shape (ellipticity) represents the mobilities of the electrons in that energy state. Associated with each valley are the electron mobility directions (parallel or perpendicular to the axes) as designated in the figure, each represents a magnitude determining the shape of the ellipsoid. The ellipsoid geometry is insured since the mobility in each perpendicular direction must be greater than the mobility in the parallel direction. In the normal or unstrained equilibrium condition, all six valleys (only three are shown) are equally populated with electrons. The contribution of each valley to the mobility depends on the orientation of the valley with respect to the applied field. The average mobility for no strain $\mu_{av}(0)$ when averaged over all six valleys is isotropic and is represented by:

$$\mu_{av}(0)=\frac{2\mu_{\perp}+\mu_{\parallel}}{3} \quad (1)$$

For silicon at room temperature

$$\mu_{\perp}\cong 5\mu_{\parallel}$$

hence

$$\mu_{av}(0)\cong 73\%\mu_{\perp}$$

If tension is applied in the [100] direction, the [100] valley rises in energy while the other two vallys (**2** and **3**) fall (neglecting the three valleys not shown which will reflect the same change). As a result of the difference in energies, a fraction, Δ, of electrons is transferred to the two lower valleys. Since

$$\mu_{\perp}>\mu_{\parallel}$$

the [100] direction in valleys **2** and **3**, a perpendicular mobility direction, is a "fast" direction as opposed to the parallel mobility direction of valley **1**. Consquently, the average mobility with a tension along the [100] axis, $\mu_{av}(\Delta)$ increases in the [100] direction. Associated with an increase in population of valleys **2** and **3** and a decrease in valley **1** is a decrease in mobilities normal to the [100] direction. This is true since perpendicular mobilities for a [100] strain are most ffective with a high population in valley **1**. If sufficient tension is applied along [100] substantially all the electrons leave the **1** valley. The mobilities after the change in population states are then:

$$\mu_{av}(\Delta)\text{ parallel to }[100]=\mu_{av}(\Delta)_{\parallel}=\mu_{\perp}$$

$$\mu_{av}(\Delta)\text{ perpendicular to }[100]=\mu_{av}(\Delta)_{\perp}=\frac{\mu_{\perp}+\mu_{\parallel}}{2}$$

Since

$$\mu_{av}(0)\cong .73\mu_{\perp}$$

the incrase in mobility effected by this strain condition parallel to [100] is approximately 37%. The decrease in mobility in the perpendicular direction is, in this case, not quite so profound but is significant, amounting to approximately 18%.

These effects result from a tensile strain parallel to the [100] direction. The effect of a compressive strain in this direction is even more striking. Such a strain transfers substantially all the electrons into the [100] valley. The mobilities are then extremely anisotropic, being:

$$\mu_{av}(\Delta)_{\parallel}=\mu_{\parallel}$$

$$\mu_{av}(\Delta)_{\perp}=\mu_{\perp}$$

The mobility perpendicular to the direction of strain is approximately 37% greater than $\mu_{av}(0)$. This is the same as the differential mobility exhibited by the

$$\mu_{av}(\Delta)_{\parallel}$$

under tension; however, the decrease in mobility in the direction parallel to the strain is almost 73%.

It is significant to note that the electron mobilities are maximum perpendicular to the direction of strain when the strain is compressive; however, the maximum is parallel to the direction of applied strain when the strain is tensile.

In the discussion we have considered variations in mobilities in n-type silicon. Other semiconductors exhibit this same phenomenon although the valleys may assume diffrent orientations in the crystal. For n-type germanium there are four valleys lying on the <111> axes. The relation between

$$\mu_{\perp} \text{ and } \mu_{\parallel}$$

at room temperature is approximately.

$$\mu_{\perp}=16\mu_{\parallel}$$

The greatest anistropy in directional mobilities in this crystal is when all the electrons are in one valley, a condition obtainable with compression along the [111] direction. Then:

$$\mu(\Delta)_{\parallel} \text{ (to [111])}=\mu_{\parallel}=\frac{\mu_{\perp}}{16}$$

$$\mu(\Delta)_{\perp} \text{ to [111]}=\mu_{\perp}$$

Since $\mu_{av}(0)$ is again given by Equation 1, the decrease in mobility parallel to [111] (with a compressive strain in the (111) direction) is over 90% while the increase in mobility perpendicular to the applied strain is approximately 45%.

Tension along [110] in germanium will raise two of the valleys and lower the other two. If the raised valleys are completely emptied, then:

$$\mu(\Delta)_{\parallel} \text{ (parallel to [110]}=_{\perp}$$

$$\mu(\Delta)_{\perp}(\perp \text{ to [110] in the } [1\bar{1}0] \text{ direction})$$

$$=0.67\mu_{\parallel}+0.33\mu_{\perp}$$

$$=.37\mu_{\perp}$$

Tension along [111] in germanium will empty the [111] valley of electrons. Then:

$$\mu(\Delta)(\parallel \text{ to [111]})=0.11\mu_{\parallel}+0.89\mu_{\perp}\cong 0.9\mu_{\perp}$$

$$\mu(\Delta)(\perp \text{ to [111]})=0.45\mu_{\parallel}+0.55\mu_{\perp}\cong 0.58\mu_{\perp}$$

It is thus seen that the mobilities of carriers in n-type semiconductors, for instance, germanium and silicon, exhibit variations in magnitude responsive to various directional strains. The many-valley theory is not directly applicable to p-type silicon or p-type germanium; however, measurements indicate that the piezoresistive effect is opposite to that of n-type germanium (i.e., tension in p-type Ge or p-type Si is equivalent to compression in n-type Ge) and the directionality of the strain to provide maximum hole mobility increase is also a [110] direction.

Certain other semiconductors exhibit, to varying degrees, this property of variation in mobilities with directional strains. Other specific materials in which this phenomenon has been observed are InSb and GaSb.

The table presents examples of semiconductor materials which provide the unexpected functions of this invention when employed as prescribed. This includes specific data relating the mobility variation in the indicated materials responsive to a given tensile strain value.

Table

Example	Material	Resistivity Type	Resistivity (ohm-cm.)	Temperature, ° K.	Orientation	M	$+\Delta\mu/\mu$ (percent)	ϵ
1	Si	p	>0.1	190	[111]	280	10	3.6×10^{-4}
							56	2×10^{-3}
							14	5×10^{-4}
2	Si	n	12	300	[100]	−133	10	*7.5×10^{-4}
							25	*2×10^{-3}
							6.7	*5×10^{-4}
3	Ge	p	15	300	[111]	102	10	9.8×10^{-4}
							20	2×10^{-3}
							5.1	5×10^{-4}
4	Ge	n	16.6	300	[111]	−157	10	*6.4×10^{-4}
							23	*2×10^{-3}
							7.9	*5×10^{-4}
5	GaSb	n	0.004	300	[111]	62	10	1.6×10^{-3}
							13	2×10^{-3}
6	InSb	p	0.010	300	[100]	74.5	10	1.3×10^{-3}
							15	2×10^{-3}

* Tension.

The mobility variation $\Delta\mu/\mu$ is related to the strain ϵ by the elastoresistive constant M according to the formula:

$$\epsilon M=\frac{-\Delta\mu}{\mu} \qquad (2)$$

For n-silicon and n-germanium, which obey valley-models, it is necessary to take account of the non-linearity effects which occur at large strains when certain of the valleys are nearly empty. For such cases the relation between $\Delta\mu/\mu$ and ϵ is given by:

$$\frac{\Delta\mu}{\mu}=\left(\frac{\Delta\mu_{max.}}{\mu}\right)\left(1-e^{\frac{-\epsilon M}{\Delta\mu_{max.}/\mu}}\right) \qquad (3)$$

where $\Delta\mu_{max.}$ is the value of $\Delta\mu$ obtained when all the electrons have been removed from the valley parallel to the stress axis. This expression applies to the values of $\Delta\mu/\mu$ in the table for Examples 2 and 4 and for strain, ϵ, of 2×10^{-3}.

As is apparent, certain of the constants M are negative in value. This merely indicates that the strain necessary to achieve the mobility variation is opposite as shown by the asterisks in the table. From the large deviations in response evident from the table it is apparent that large variations in strain values may be required to achieve the same results in two different materials. Thus it is difficult to prescribe a particular strain value as defining the essential requisite of this invention. More appropriate definition is presented by the degree of mobility variation itself. Accordingly, the unexpected advantages of this invention are obtained when a junction device is purposely subjected to a directional strain in a manner such as to obtain an increase or decrease in the carrier mobility of the device having a magnitude of at least 10%. A preferred minimum strain magnitude for achieving this result is approximately 2×10^{-3}. From Equation 2 the elastoresistive constant M required to provide a

10% mobility variation with a strain value of 2×10^{-3} is approximately 50. For the purposes of this invention the semiconductor material in which significant carrier mobility improvement is to be obtained must have an elastoresistive constant of at least 50. Various other semiconductor materials which possess this essential requisite and are thus capable of exhibiting the attractive features described herein are intended to be within the scope of this invention.

The above-described phenomenon is utilized according to this invention by assembling various devices which include p-n junctions with inherent strains as dictated by the principles above set forth to the end that desirable properties of the device are emphasized or enhanced. The following embodiments are given as illustrative of devices utilizing these principles.

A particular embodiment employing this principle is described with respect to the construction of an n-p-n transistor. The primary accepted desideratum in such devices is a high gain-bandwidth product. For a given semiconductor, the gain-bandwidth product, GB, for an n-p-n transistor of optimum design is:

$$GB=\frac{A}{\sqrt{K}}\mu_p\mu_n \quad (4)$$

where μ_n and μ_p are the mobilities of electrons and holes in certain specified regions of the transistor, respectively, K is the dielectric constant, and A is also a constant. Since μ_n is inversely proportional to the transit time of electrons across the base layer, the value of μ_n, therefore, is significant primarily in the direction normal to the plane of the base layer. On the other hand, μ_p is inversely proportional to the resistance of the base layer to current flow in the direction of the plane of the base layer. Therefore, since the base layer conduction is mainly by hole carriers, and since a low resistance is desired in the plane of the base layer, it is desirable to have large values of μ_p in the direction of the plane of the base layer. By proper control of strains purposely introduced in the base layer, both of these desiderata can be obtained.

FIG. 2 shows a device constructed according to this embodiment illustrating one manner of obtaining the desired strain. An n-p-n mesa transistor is shown having a base block **4** of any appropriate material, for instance, molybdenum or Kovar. Mounted on the base block and attached thereto at one extremity thereof is a germanium wafer **5** carrying an n-p-n mesa transistor indicated generally at **6**. The Ge wafer **5** is attached to the base block by solder **7** or other appropriate means. At the other extremity of the base block **4** is a vertical protrusion **8** designed to bear against the Ge wafer in such a manner as to cause a bending in the wafer and a resulting compressive strain in the mesa. The effects of the strain in the mesa transistor are better appreciated from an examination of FIG. 3 which is a detailed view of the mesa of FIG. 2. FIG. 3 shows in detail a conventional n-p-n mesa transistor comprising an n-type Ge wafer collector **10** carrying p-type base layer **11** having base contact **12** of heavily doped p-type material and emitter **13** of n-type material attached thereto. The normal carrier current in the base layer **11** is shown by the arrows from each contact. The conduction time of electrons through the base layer indicated by the arrows from emitter **13** is determined by the mobility of electrons in a direction normal to the plane of the base layer while the flow of holes from the base contact is determined by a hole mobility which, as indicated by the arrows, is primarily in the direction of the plane of the base layer. Since, as set forth above, a longitudinal compressive strain in the base layer (assuming proper crystal orientation) produces both an increase in μ_p in the direction of the plane of the base layer and an increase in μ_n transverse to the plane of the base layer, the gain-bandwidth product is significantly increased. In other words, a strain in the base layer in the [111] crystallographic direction (as shown) produces an increase in the mobility of electrons across the layer while simultaneously producing an increase in mobility of holes in the [111] direction. In the embodiment shown, the strain in the base layer is a compression in the [111] direction. In view of the increase in maximum mobility set forth previously for this directional strain, the mobility increase in the n-type material (adjacent the emitter) is approximately 45%. This value, as stated above, is based upon a strain sufficient to transfer all the electron carriers to the valley situated on the (111) axis. The actual strain magnitudes preferred for these materials is approximately 90% of that maximum due in part to the fracture point of the material and also due to the fact that the effect is represented by an asymptotic curve rendering the last 10% relatively insignificant. Accordingly, the percentage value of the mobility increase must be revised to $90\%\cdot45\%\cong41\%$. The increase in the hole mobility due to compressional strains in the [111] direction is not as easily predicted since, as stated previously, the many-valley theory is not consistent in p-type germanium. However, from experimental measurements, the increase in hole moblity in the base layer for a similar strain of 90% of the value required to obtain the maximum mobility increase is approximately 27%. Inserting these increases in Equation 3, the following increase in gain-bandwidth product is obtained:

$$GB_0=\frac{A}{\sqrt{K}}\cdot\mu_n\cdot\mu_p$$

$$GB'=\frac{A}{\sqrt{K}}(1.41\mu_n)(1.27\mu_p)$$

$$GB'=GB_0\times(1.79)$$

or an increase by a factor of 79%.

Another very significant advantage of such a strain is that it also serves to increase the current multiplication factor of the device (ratio of electron current to total current of holes and electrons across the base layer at the emitter—commonly designated the gamma factor) since μ_n in the direction transverse to the base layer is increased while μ_p transverse to the base layer is decreased.

The required strains such as those prescribed in the table are obtainable in many ways, one of which is by differential expansion as suggested in the embodiments presented here. More elaborate strain magnifications can be realized using the principles of United States Patent No. 3,009,126 issued November 14, 1961.

It should be noted that the sensitivity of mobility to strain increases at lower temperature and decreases at higher temperature. Thus, for a temperature significantly lower than 300° Kelvin, the required strain will be significantly less.

The previous embodiment presupposes that the crystal orientation of the base layer is such that the plane of the mesa lies in the [111] direction. In many of the present fabricating techniques, the plane of the mesa is a (111) plane which would then be perpendicular to a [111] direction. Consequently, for n-p-n mesa transistors fabricated in this manner, the direction of a unidirectional compressional strain would appropriately be a $(1\bar{1}0)$ direction or a $(11\bar{2})$ direction, or any other direction in the (111) plane. The consequence of this change in orientation is, approximately, a 30% increase in strain necessary to obtain 90% of the electrons in one valley, the condition assumed previously.

Similar changes in μ_n and μ_p can be produced in the n-p-n transistor of the form shown in FIGS. 4A and 4B. FIG. 4A shows a base block **21** carrying the n-p-n transistor. The transistor is characterized by n-type collector **22**, n-type emitter **23**, and the p-type base layer **24**. Appropriate leads are indicated at **25** and **26**. The transistor is firmly attached to the base block by solder **27** or other appropriate means. These elements can perhaps be better seen in the plan view, FIG. 4B. The [111] crystal direction is as indicated with relation to the p-type base region semiconductor material. In this embodiment the desired changes in μ_n and μ_p are attained with a tensile strain which is again preferably introduced during fabrication. Differential expansion may be used or the base block may be bent around fulcrum "A" after the bond between the transistor and the base block is formed.

Another embodiment of particular practical interest concerns a p-n-p mesa transistor. Somewhat analogous to the n-p-n mesa transistor embodiment described above, the desired strain in the p-n-p transistor is, however, a radial tensile strain in the plane of the base layer. The same desirable mobility variations as set forth in connection with the n-p-n embodiment are obtained with a reverse strain, i.e., a tensile strain. A typical p-n-p transistor is shown in FIG. 5. Such a device and an appropriate fabrication procedure are described as follows:

A base pin **30** of molybdenum or Kovar or other appropriate material is initially strained in the directions indicated by the arrows. Bi-axial tension has generally been found to give superior advantages over uni-axial strains; consequently, the base material is preferably strained in two directions as shown. A p-type germanium wafer **31** whose surface lies in the (111) plane is mounted on base pin **30**. The wafer **31** carries the mesa which is made up of an n-type base layer **32** having p-type emitter **33** and n-type base contact **34** affixed thereto. After the wafer **31** which carries the base layer **32** has been soldered to the pin **30** and the solder has hardened, the strain on the pin is relieved, thus imparting a biaxial tension in base wafer **31** with an attendant biaxial tension in base layer **32**. It should be noted that a biaxial tensile strain is twice as effective as a unidirectional tensile strain. Hence, straining methods that produce biaxial strains are particularly effective. The tension in the plane of the base layer **32** provides for the desired mobility variations. According to the principles above set forth, this strain increases the mobility of holes in a direction transverse to the base layer while simultaneously increasing the electron mobility in the direction of the plane of the base layer.

In both of these techniques, the solder must be a hard solder such as a gold-germanium alloy so that the strain imparted to the pin is effectively translated to the base layer.

A further embodiment of this invention concerns the improvement of the RC characteristic of a varactor diode. Varactor diodes typically are p-n junctions having an alloy or diffusion region very heavily doped as opposed to the doping level in the base material. The RC (resistance-capacitance) product is primarily determined by the properties of the base material. Reducing the RC product is desirable in that higher frequency of operation when used as a mixer, parametric amplifier, or variable capacitor becomes possible; and also in that lower noise when used as a parametric amplifier is possible at a given frequency.

As the concentration of impurity in the heavily doped n-type base region is increased, the resistance R decreases as desired; however, the capacitance, C, increases. Increased impurity levels are desirable in that as the doping is increased, the decrease in R predominates over the increase in C resulting in a lower RC product. However, at high impurity concentration levels, scattering of electrons by the impurity decreases the electron mobility. The point just below which impurity scattering becomes significant is considered the optimum donor concentration. From this it follows that an increase in electron mobility in a direction normal to the junction permits a higher optimum impurity concentration level thus enabling further reductions in the RC product. This increase in electron mobility can be achieved according to this invention by straining the base layer in a particular manner. One manner of obtaining the necessary strain in a typical germanium varactor diode is shown in FIG. 6. The n-type base region **40** having a heavily doped base contact **41** along the lower surface thereof is attached to base block **42** by solder **43** or other appropriate means. Electrode **44** and the heavily doped p-region **45** contact the base layer as shown. According to the principles as set forth above, a compressive strain in the [111] direction as indicated will increase the mobility of the carriers in the direction of electron flow. The compressive strain is preferably built into the device during fabrication by straining the base block under tension, soldering the wafer while the block remains stretched, allowing the solder to harden, and relieving the strain on the base block thus imparting a compressive strain in the wafer. Alternatively, the same result may be obtained by heating the base block, soldering or otherwise attaching the base layer, and then cooling the base block. Variations on the amount of strain so produced may be obtained by a control of the temperature to which the base block is heated during the fabrication procedure or by judicious selection of the coefficient or thermal expansion of the base block relative to that of the base layer. The decrease in the RC product of the diode so obtained approximates the increase in mobility. For this particular case, the decrease in RC product is approximately 45%.

The devices for which this invention is adapted are generally those devices which depend for their operation on at least one p-n junction.

As is apparent to one skilled in the art, the device modifications and improvements made possible by this invention are too numerous to set forth in their entirety; however, any semiconductor device employing directional strains purposely introduced such that the strain as applied to the crystallographic orientation of a semiconductor material as previously defined results in a significant increase or decrease in carrier mobility adjacent an active junction is considered within the scope of this invention. For the purposes of this invention, a significant increase or decrease, as desired, in carrier mobility is considered to be at least 10%.

Whereas each material has a characteristic crystallographic direction along which strains are most effective in producing variations in mobilities, it is obvious that strains may be exerted along directions which are small departures from that preferred direction and still produce significant mobility variations.

Various other modifications of this invention will become apparent to those skilled in the art. All such variations and deviations which basically rely upon the fundamental and applied concepts through which this invention has advanced the art are properly considered to be within the scope of this invention.

What is claimed is:

1. An improved transistor comprising an n-p-n germanium transistor in which the direction of electron flow from the emitter to the collector through the p-type base layer is approximately perpendicular to the [111] crystal direction of the base layer and the direction of hole carriers through the base layer from base to emitter is approximately parallel to the [111] crystal direction of the base layer and means associated with said transistor for applying a permanent elastic compressive stress to the p-type base layer below its elastic limit approximately in the [111] crystal direction said stress being sufficient to increase the carrier mobility in the base layer by at least 10%.

2. An improved transistor comprising an n-p-n germanium transistor in which the direction of electron flow through the p-type base layer from emitter to collector is in the [111] crystal direction of the base layer and means associated with said transistor for applying a permanent elastic compressive stress to the p-type base layer below its elastic limit in a crystal direction in the (111) crystal plane said stress being sufficient to increase the carrier mobility in the base layer by at least 10%.

3. An improved transistor comprising an n-p-n silicon transistor in which the direction of electron flow through the p-type base layer from emitter to collector is in the

[111] crystal direction of the base layer and means associated with said transistor for applying a permanent elastic compressive stress to the p-type base layer below its elastic limit in a crystal direction in the (111) crystal plane said stress being sufficient to increase the carrier mobility in the base layer by at least 10%.

4. An improved transistor comprising an n-p-n germanium transistor in which the direction of electron flow through the p-type base layer from emitter to collector is in the [111] crystal direction of the base layer and means associated with said transistor for applying a permanent elastic tensile stress to the p-type base layer below its elastic limit in a crystal direction in the (111) crystal plane said stress being sufficient to increase the carrier mobility in the base layer by at least 10%.

5. An improved transistor comprising an n-p-n silicon transistor in which the direction of electron flow through the p-type base layer from emitter to collector is in the [111] crystal direction of the base layer and means associated with said transistor for applying a permanent elastic tensile stress to the p-type base layer below its elastic limit in a crystal direction in the (111) crystal plane said stress being sufficient to increase the carrier mobility in the base layer by at least 10%.

6. An improved semiconductor device including at least one p-n junction, said junction comprising an n-type region containing an n-type impurity and a p-type region containing a p-type impurity, the semiconductor materials forming said regions being selected from the group consisting of Ge, Si, InSb and GaSb, means for applying a permanent directional elastic stress to at least one of said regions below its elastic limit, said stress applied to produce a strain of at least 2×10^{-3}, said strain oriented with respect to the crystallographic axes of the material so as to produce a variation in carrier mobility of at least 10%.

7. The device of claim **6** wherein the semiconductor material is selected from the group consisting of Si and Ge and the stress produces a strain of at least $5 \cdot 10^{-4}$.

8. The device of claim **6** wherein the semiconductor material is germanium and the direction of the stress is essentially the [111] crystallographic direction.

9. The device of claim **6** wherein the material is germanium and the direction of the stress is essentially perpendicular to the [111] direction.

10. The device of claim **6** wherein the semiconductive material is silicon and the direction of the stress is essentially the [100] crystallographic direction.

11. The device of claim **6** wherein the semiconductor material is silicon and the direction of the stress is essentially perpendicular to the [100] direction.

12. The device of claim **6** wherein the semiconductor material is silicon and the direction of the stress is essentially the [111] direction.

13. The device of claim **6** wherein the semiconductor material is silicon and the direction of the stress is essentially perpendicular to the [111] direction.

14. An improved transistor including a base layer and collector and emitter regions, said base layer comprising a semiconductor material selected from the group consisting of Ge, Si, InSb, and GaSb, and means for applying a permanent directional elastic stress to the base layer below its elastic limit, said stress producing a strain of at least 2×10^{-3}, said strain oriented with respect to the crystallographic axes of the semiconductor material in the base layer such that the mobility of carriers in the base layer is altered by a magnitude of at least 10%.

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