United St[ates Patent]

Flippen

[11] 3,799,648

[45] Mar. 26, 1974

[54] **FERROELASTIC CRYSTALS SWITCHED BY MOTION OF A DOMAIN WALL HAVING A ZIGZAG CONFIGURATION**

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[22] Filed: **Dec. 26, 1972**

[21] Appl. No.: **318,502**

[52] **U.S. Cl.** .... **350/150,** 350/151, 350/160, 23/293, 423/263, 340/173 LS

[51] **Int. Cl.** **G02f 1/26**

[58] **Field of Search** .... 350/150, 151, 160, 287, 350/161; 23/301 SP, 305, 293; 423/21, 263; 340/173.2, 173 LS

[56] **References Cited**

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Primary Examiner—Ronald L. Wibert
Assistant Examiner—Michael J. Tokar

[57] **ABSTRACT**

Described are devices employing a ferroelastic crystal having two spontaneous strain states separated by a zigzag domain wall which can be switched to increase one strain state at the expense of the other by motion of the zigzag wall as a whole. Zigzag walls can be created by applying high stress to ferroelastic crystals under conditions which inhibit formation of normal planar walls. Once formed the zigzag walls are stable in the absence of applied stress and can be moved through the crystal by conventional means. The use of such a device in an optical shutter is also described.

10 Claims, 10 Drawing Figures

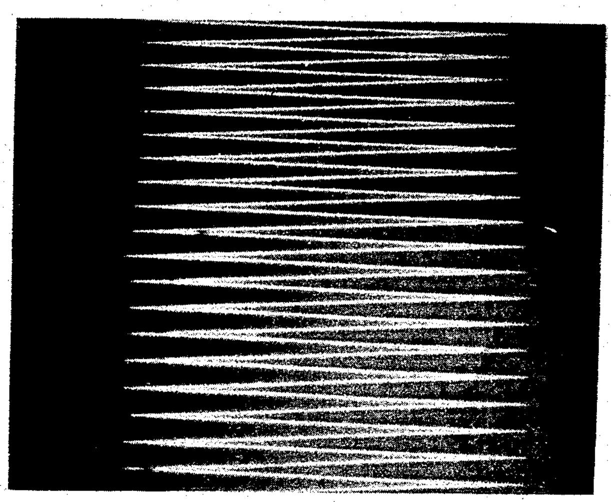


FIG. 1

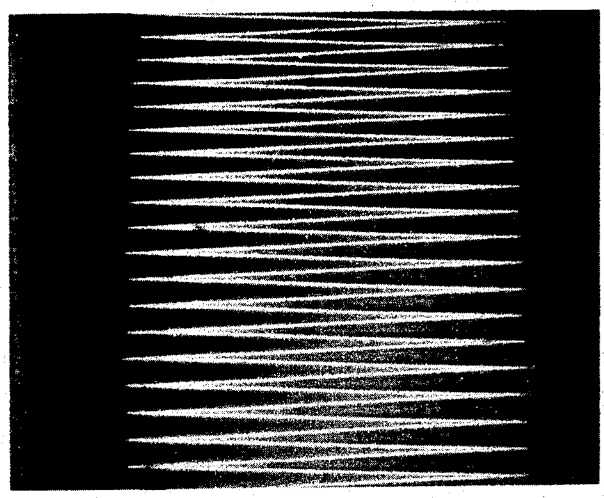


FIG. 2

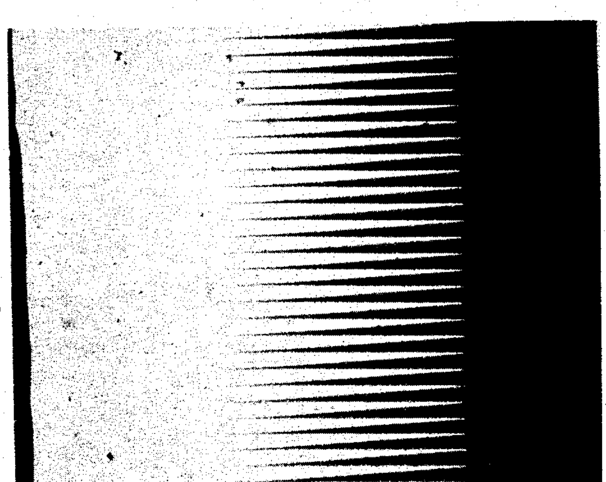


FIG. 3

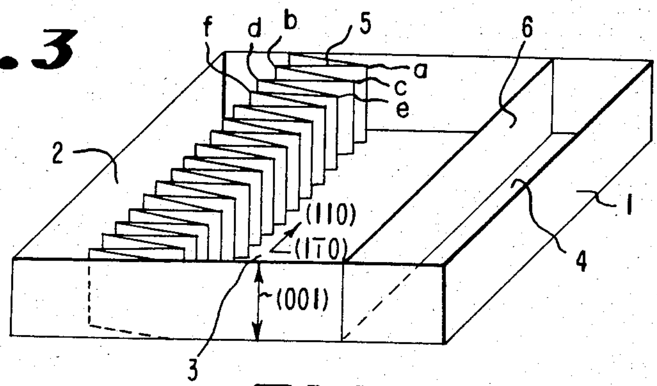


FIG. 4

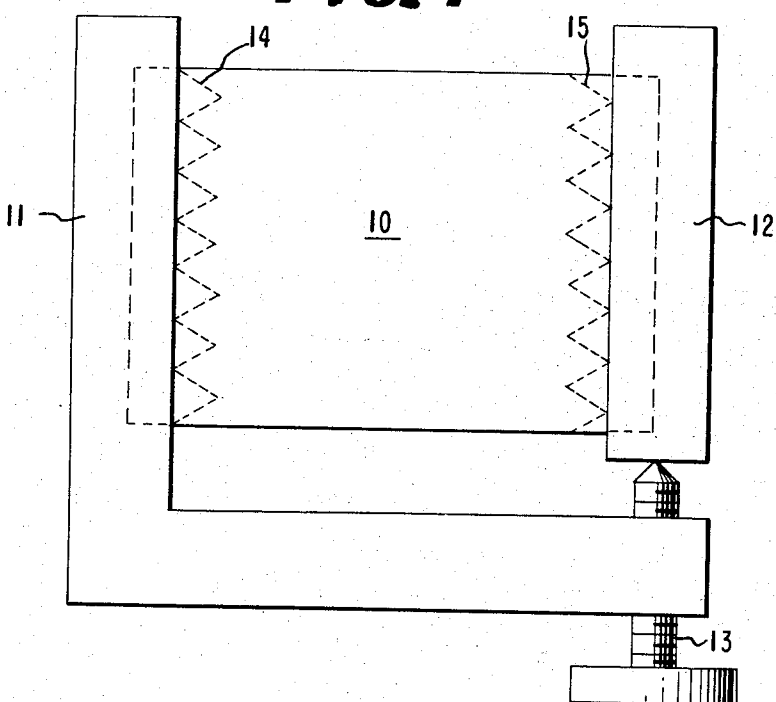


FIG. 5a

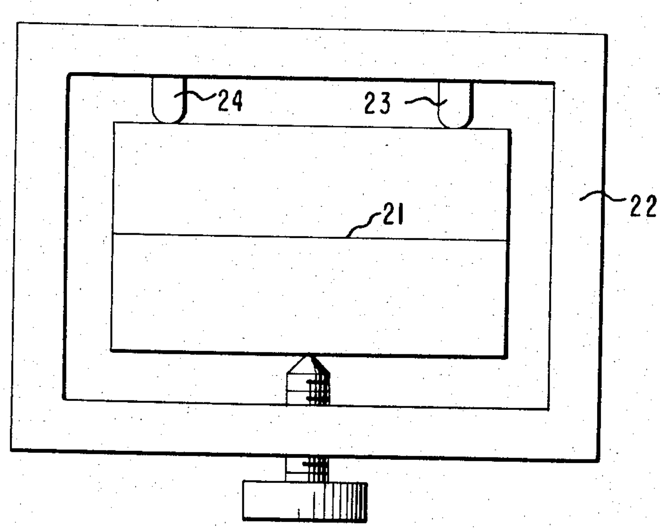


FIG. 5a

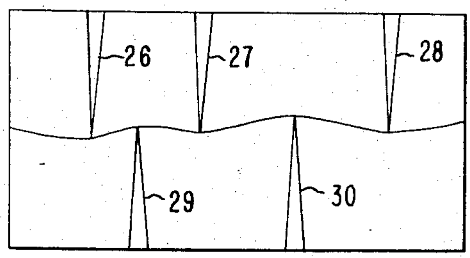


FIG. 5c

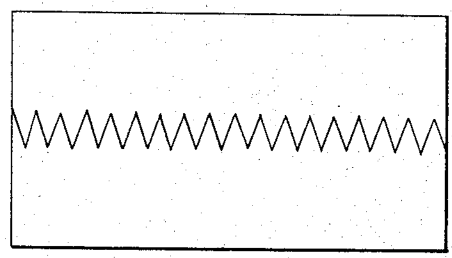


FIG. 6

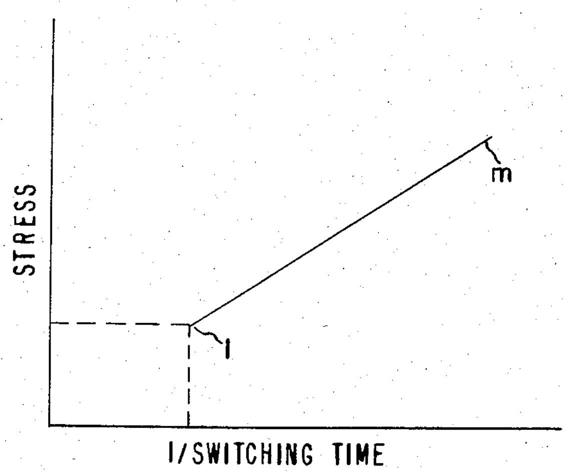


FIG. 7

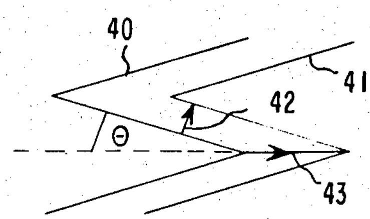
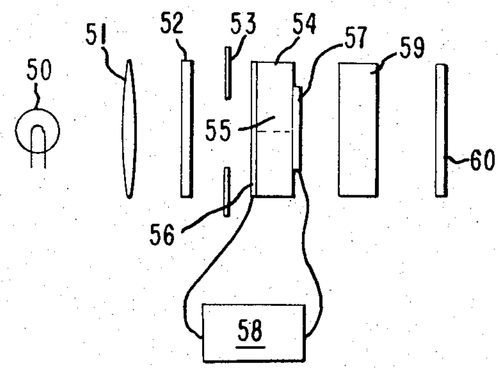


FIG. 8



FERROELASTIC CRYSTALS SWITCHED BY MOTION OF A DOMAIN WALL HAVING A ZIGZAG CONFIGURATION

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to devices utilizing the switching properties of ferroelastic crystals wherein the crystal is switched from one state of spontaneous strain to a second and different state of spontaneous strain.

2. The Prior Art

The existence of ferroelasticity was first clearly recognized by Aizu, J. Phys. Soc. Japan, Vol. 27, page 387 (1969). According to Aizu, a crystal is said to be ferroelastic when it has two or more spontaneous strain orientation states in the absence of mechanical stress and can be switched from one orientation state to another by mechanical stress. The states are identical or enantiomorphic in crystal structure and different in mechanical strain tensor at null mechanical stress. A plot of stress versus strain for such materials exhibits a hysteresis loop similar to that of ferromagnetic materials. Also, like ferromagnetic materials, ferroelastic materials usually exhibit a Curie temperature above which the ferroelastic properties are absent and a new phase of different crystal structure is present.

Ferroelastic materials are divided into domains throughout which the strain tensor is the same. Two domains which differ in the strain tensor generally interface at one of two possible mutually perpendicular domain walls which tend to be highly planar, and lie in distinct crystallographic planes. Such walls tend to extend completely across the crystal. In switching, one domain grows at the expense of a neighboring domain. With walls of the type hereinabove discussed, switching is usually accomplished by motion of the domain walls in a direction perpendicular to their plane.

The different strain states are thermodynamically equivalent and equally stable. The phenomenon of switching takes place because the energy barrier between the states is small. This implies that the ferroelastic strain states are each a slightly distorted form of a certain prototype state of higher symmetry. In most cases, the prototype state is the state of the crystal above the Curie point transition temperature. The symmetry of the prototype state can be deduced from the symmetry of the ferroelastic state and the domain structure (Aizu, J. Phys. Soc. Japan, Vol. 27, 387 (1969)) and hence the possible species possessing ferroelasticity can be classified in terms of the point group symmetry of the prototype and the point group symmetry of the ferroelastic species. In Aizu's notation, the point group symmetry of the prototype species is first written followed by F and then the symmetry of the ferroelastic species.

Conversely, following the procedure followed by Shuvaloff, J. Phys. Soc. Japan 28 (Supplement) page 28 (1970) for ferroelectric materials, the domain wall orientations can be deduced from the symmetry of the prototype point group, and the point group of the ferroelastic phase.

A crystal is said to be ferroelectric if it exhibits the spontaneous switchable electric dipole moment. In the absence of an externally applied electric field, the electric polarization corresponding to the dipole moment can have two or more orientations and can be shifted

from one orientation or state to another by the external application of an electric field. Ferroelectric materials exhibit a hysteresis loop in a plot of electric polarization versus electric field and generally display a transition temperature called the Curie temperature above which the material is paraelectric.

Aizu (op cit.) has recognized coupled ferroelastic/-ferroelectric materials wherein ferroelastic domains coextensive with the ferroelectric domains exist and which have the same Curie temperature for the ferroelectric and ferroelastic properties. Such crystals can be switched by the application of either electrical or mechanical stress. Domain structures and domain walls are, however, dictated by the ferroelastic properties.

Crystals having coupled ferroelectric/ferroelastic properties have been employed heretofore in devices utilizing the switching properties whereby the crystal can be switched from one ferroelectric/ferroelastic state to another, by an electric or mechanical stress and wherein the change in state is detected by electrical or optical means as shown, for example, in U. S. Pat. Nos. 3,623,031, 3,661,442, 3,559,185, 3,602,904, and 3,614,754.

The switching of crystals having ferroelastic properties by the nucleation and lateral motion of planar domain walls is a relatively slow process. Thus, utilizing the optical properties of the domains, it has been proposed to construct optical shutters of the ferroelastic/-ferroelectric material gadolinium molybdate. The speed of such shutters, however, is limited to about the speed attainable with conventional mechanical shutters.

SUMMARY OF THE INVENTION

The present invention comprises a crystal of a material having ferroelastic properties, said crystal having a domain wall extending across the crystal in a zigzag configuration, and means to move said domain wall whereby a substantial portion of said crystal is switched from one ferroelastic strain state to a second ferroelastic strain state.

Preferred crystals having ferroelastic properties are coupled ferroelastic/ferroelectric crystals and especially those crystals exhibiting uniaxial spontaneous electric polarization. Particularly preferred are crystals of the rare earth molybdates having the β'-gadolinium molybdate structure, especially β'-gadolinium molybdate itself. This invention also comprises methods of making the aforesaid zigzag domain walls in crystals having ferroelastic properties by applying a shear stress to such crystals under conditions inhibiting the formation of ordinary planar domain walls. Such methods include:

1. Clamping regions adjacent opposite edges of a single domain crystal of a material having ferroelastic properties to inhibit deformation of the crystal in the clamped regions, the edges of the clamped regions having boundaries with the central unclamped region parallel to a twinning plane in the material and applying an increasing shear stress across the unclamped region of the crystal parallel to the said boundaries until domain walls form having a zigzag configuration.

2. Applying an increasing bending stress across the single crystal of a material having ferroelastic properties, said crystal being divided into a first domain and a second domain by a normal planar domain wall, the bending shear stress being perpendicular to said do-

main wall and increasing until said normal domain wall transforms to a zigzag configuration.

THE DRAWINGS AND DETAILED DESCRIPTION OF THE INVENTION

There has now been discovered a new type of domain wall which can be induced in crystals having ferroelastic properties, and which is stable in the sense that, one formed, such walls exist in the absence of applied electrical-mechanical stress and can be moved back and forth in crystals as an entity by stress or in the case of coupled ferroelectric/ferroelastic species, by electrical fields. Because of their appearance and properties, this type of wall has been named a zigzag wall. The mobility of zigzag walls is substantially greater than that of normal walls; indeed wall mobilites thirty times or more greater than conventional walls have been achieved.

This invention will be better understood by a reference to the drawings which accompany the specification and in which:

FIG. 1 is a microphotograph of a zigzag wall in a half-wave plate of gadolinium molybdate.

FIG. 2 is a microphotograph of a zigzag wall in a quarterwave plate of gadolinium molybdate.

FIG. 3 is a sketch of the zigzag wall with the principal dimensions indicated.

FIG. 4 illustrates one method of creating zigzag walls in a plate of a crystalline material having ferroelastic properties.

FIG. 5*a*, 5*b* and 5*c* illustrate another method of making a zigzag wall.

FIG. 6 is a graph illustrating wall velocity versus applied stress for a domain wall in a ferroelastic material.

FIG. 7 illustrates the motion of the zigzag wall across the crystal.

FIG. 8 shows an optical switch using a crystal of a material having ferroelastic properties and containing a zigzag wall of the present invention.

In FIG. 1 is shown a microphotograph of a zigzag wall in a half-wave plate made of β'-gadolinium molybdate which is a coupled ferroelectric/ferroelastic material having Aizu species 42mFmm2. The plate is cut perpendicular to the *c* axis, that is, the [001] axis of electric polarization. The photograph was made with polarized light with both polarizer and analyzer aligned parallel to one of the [110] planes whereby light transmitted by both domains is extinguished. The polarization properties of the crystal plate in the vicinity of the domain wall differ from those of the surrounding domains when the domain wall is observed as a white line on a dark field. The general line of the zigzag wall is parallel to a [110] direction and the wall moves substantially as an entity along the other of the [110] planes, on application of either electrical or mechanical stress tending to favor one of the domains separated by the wall.

FIG. 2 is a microphotograph of a quarter-wave c-cut plate of β'-gadolinium molybdate divided into two domains by a zigzag wall. The photograph is taken with polarized light using a circular analyzer and arranged so that light transmitted by one domain is extinguished while light passing the other domain is transmitted. With this optical arrangement crystals of β'-gadolinium molybdate can be employed as an optical switch or shutter.

Turning now to FIG. 3, there is shown a sketch of a crystal of a rare earth molybdate such as gadolinium molybdate, cut to a c-cut plate with edges parallel to the [110] set of planes. The crystallographic directions are indicated on the figure. The plate 1 is divided into three domains, 2, 3 and 4, by a planar domain wall 6 and a zigzag wall 5, the edges *a*, *c* and *e*, etc. forming the tips of the zigzag are substantially aligned in a plane which is a twinning plane capable of supporting a normal domain wall such as a domain wall 6. Likewise, the edges *b*, *d* and *f* also lie in a plane parallel to the twinning plane of the normal domain wall, 6. The distance between the planes containing the edges *a*, *c*, *e* and the plane containing the edges *b*, *d*, *f* will be called the width of the wall, *w*. Width *w* can vary widely, even for the same material. For example, in gadolinium molybdate, *w* can be from 100 to 4,000 microns. The distance between the edges of the zigzag such as *a* to *c*, *c* to *e*, *b* to *d*, or *d* to *f* are highly uniform for a given wall. This distance can be called the pitch, *p*. Again, the pitch can vary substantially even in crystals of the same material. For gadolinium molybdate, the pitch is between 5 and 150 microns.

The ratio of the pitch to the width is less variable and is generally between 0.05 and 0.15. The walls, such as the wall between edge a and edge b which form the zigzag, appear to slightly sygmoid in shape but can be approximated closely by planes. The planes lie at equal angles from the (110) twinning plane perpendicular to the (110) twinning plane in which domain wall 6 lies. Assuming that the zigzag wall is composed of planar segments, the angle θ can be calculated from the relation to $\tan \theta = p/2w$, thus from the aforesaid values of p/w, θ is from about 1.5° to 4.5° in the rare earth molybdates, such as gadolinium molybdate. In general, p/w decreases with *w*.

Turning now to FIG. 4, in FIG. 4 is shown a c-cut crystal of gadolinium molybdate 10 having its edges cut parallel to the [110] planes. A fixed clamp 11 is cemented along one edge of the crystal and a movable clamp 12 is cemented along the opposite edge so that the edges of the clamps are parallel to (110) planes. A cement should be employed which can be applied in the liquid state and hardened without substantial shrinkage so that strains are not imposed upon the crystal by hardening of the cement. The crystal is placed upon the clamps and cement is allowed to flow along the edges of the crystal by capilliary action in order to form a linear cement line between the edge of the clamp and the crystal. The regions of the crystal cemented to the clamps 11 and 12 are prevented from deforming and thus switching from one domain state to another. Thus domain walls trapped within the free region of the crystal are retained therein by the clamps 11 and 12. Clamp 11 is provided with a screw 13 bearing a clamp 12 so that pressure can be applied at clamp 12 as desired. Also, if desired, a strain gauge can be placed between the screw 13 and clamp 12 to measure the applied stress, although this is not essential. In one method of using the apparatus of FIG. 4, crystal 10 is a single domain crystal. If the crystal has ferroelectric properties, it must be electroded on the faces intersecting the ferroelectric axis and connection made between the electrodes so that the material may be manipulated like a pure ferroelastic material. Stress is then applied to the crystal 10 by tightening screw 13 against clamp 12. When a certain level of stress is attained, two zigzag domain walls 14 and 15 will form in the crystal adjacent the edges of clamps 11 and 12. In many instances, the sudden appearance of the domain walls is accompanied by an audible noise. If only one of the domain walls is required, clamp **12** may be removed by dissolving the cement in a suitable solvent. Domain wall **15** can then be expelled from the crystal by the application of stress.

Another method of making the zigzag walls of the present invention is illustrated in FIG. *5a*, *5b* and *5c*. In FIG. *5a*, the crystal **20** consists of a c-cut plate of gadolinium molybdate having its edges parallel to the **110** planes and is divided into two domains by a domain wall **21.** The crystal is placed in a frame **22** between rounded protruding lugs **23** and **24** and a screw **25** passing through the frame **22** so that a bending stress can be applied to the crystal perpendicular to domain wall **21,** on application of pressure with screw **25.** In FIG. *5a*, the crystal is shown prior to application of bending stress. In FIG. *5b*, the same crystal is shown after bending stress is applied. Blade-like domains **26, 27, 28, 29** and **30** are formed in the crystal perpendicular to the domain wall **21** and impinge thereon. The domain wall **21** appears to bend slightly as indicated where the bladelike domains impinge on it. When a critical stress is exceeded, the domain wall **21** suddenly transforms to a zigzag domain wall as shown in FIG. *5c* and the blade-like domains disappear.

The stress required to form the zigzag domain wall is substantially greater than the stress required to nucleate a planar wall in the gadolinium molybdate crystal. Typically, the zigzag domain walls are formed at pressures of 5 kg per sq. cm or more in gadolinium molybdate. Application of further stress tends to decrease the width and to a lesser extent the pitch of the zigzag wall. The exact levels of stress required varies from crystal to crystal even in the same substance. However, for a given crystal, the results appear quite reproducible.

Once formed, the zigzag wall can be manipulated by an electrical or mechanical stress in the same manner as a normal plannar domain wall. Methods of manipulating domain walls in crystals of ferroelectric/ferroelastic materials are described more completely in the copending commonly assigned application of John R. Barkley, Ser. No. 251,055. The variation of the speed of switching the crystal by movement of the zigzag wall as a function of applied stress is shown in FIG. **6.** Over the range of velocities measureable by stroboscopic techniques, i.e., between points **1** and m on the curve of FIG. **6,** the rate of switching measured by the reciprocal of the switching time is a linear function of stress.

A certain threshold stress is required before appreciable wall motion takes place, indicated in the figures by point **1.** The threshold stress appears to depend strongly on the particular crystal selected of any given material. A similar curve holds for the ordinary planar domain wall, however, for the zigzag wall the threshold stress is about the same or lower than for a normal wall and the mobility given by the slope of line *l–m* is from 10 to 30 times or more greater.

While the reason for the increased mobility of the zigzag domain walls compared with the normal planar walls is not fully understood, it is possible that it is due to a geometric factor.

FIG. **7** illustrates the geometric factors associated with the movement of the domain wall. In FIG. **7,** a portion of the zigzag wall **40** is shown at an initial location and the same wall **41** is shown after motion forward in response to stress. The motion of the essentially planar domain walls making up the zigzag wall normal to the length is indicated by a vector shown by arrow **42** whereas the motion of the zigzag wall normal to the length of the zigzag wall is given by a vector indicated by the arrow **43.** The ratio of vector **43** to vector **42** is given by cosecant θ , wherein θ is as defined hereinabove. The velocity of the essentially planar walls making up the zigzag wall normal to their face calculated from this expression is found to be essentially that of a conventional planar wall extending across the crystal. For example, in a mixed molybdate of gadolinium dysprosium, the zigzag wall is formed in a crystal wafer 0.75 mm thick and 5.5 mm wide with the space 5.0 mm long between clamps. The zigzag wall had a width w of 0.47 mm and a pitch of 65 microns between the tips of the zigzag. The wall moved at a threshold voltage of 50 volts applied to electrodes on the faces of the wafer, that is, a threshold field of 650 volts per centimeter. Measured mobility of the wall was found to be 0.280 $cm^2sec^{-1}volts^{-1}$, which is about 25 times the mobility measured for a planar wall in a crystal of this material. On the above considerations, an increase im mobility of about **15** would be expected.

More than one zigzag wall can be formed in a crystal and such walls can exist together with normal planar walls in the crystal provided the walls do not intersect. If the material has ferroelectric properties a crystal can be divided into the zones by partial electroding and the walls moved independently within each zone by application of suitable voltages to the partial electrodes. Switching zones can also be defined by clamps as illustrated above in connection with FIG. **4** to confine a zigzag domain wall to a predetermined switching region of the crystal. However, excessive electrical stress or mechanical stress applied to the zigzag adjacent the clamp will tend to alter the wall by decreasing the zone width and the pitch as explained hereinabove.

Crystals of ferroelastic materials containing zigzag walls are useful in devices such as optical switches. FIG. **8** illustrates an arrangement which cam be employed as an optical switch. In FIG. **8** there is shown a source of light **50,** a lens **51** adapted in a range to collimate the light, a polarizer **52** in the path of the collimated light, and an aperture stop **53** to limit the aperture of the device. A plate of a ferroelectric/ferroelastic material such as gadolinium molybdate **54** having a zigzag wall therein **55** is equipped with electrodes **56** and **57** on the c-cut faces thereof perpendicular to the planar zigzag wall. Electrode **56** is a transparent electrode covering substantially all of the face of the crystal, whereas electrode **57** is a rectangular electrode covering the face of the crystal along the length of the zigzag wall, but having edges parallel to the zigzag wall which are displaced from the edges of the crystal **54.** Thus on application of a voltage between electrodes **56** and **57** an electric field is created in the center of the crystal tending to move the zigzag wall but no field is created on the edges of plate **54** so that the zigzag is confined substantially to the region of the plate covered by electrode **57.** A voltage source **58** is supplied to provide an electric field of variable intensity and polarity between electrodes **56** and **57** whereby the domain wall **55** can be driven across the crystal **54** in either direction as desired. Crystal **54** is desirably cut to a thickness which provides for quarter-wave retardation for light traversing the domains of the birefringent ferroelectric/ferroelastic crystal. The light passing through crystal **54** passes through a second quarter-wave plate **59** and then through an analyzer **60.**

Plate **59** can be a quarter-wave plate of gadolinium molybdate in the form of a single domain or a quarter-wave plate of quartz or other birefringent material.

The ferroelectric/ferroelastic domains of gadolinium molybdate are biaxially birefringent with (+) $\Delta n = 3.90 \times 10^{-4}$ for $\lambda = 0.5\ \mu$. A quarter-wave plate is approximately 0.37 mm in thickness. Plane polarized light passing through the crystal **54** is converted to circularly polarized light, the sense of the circular polarization being reversed on switching the crystal from one ferroelastic strain state to the other ferroelastic strain state by motion of domain wall **55.** The circularly polarized light emerging from plate **54** is converted to plane polarized light by passage through plate **59** wherein the plane of polarization lies in one of two directions at right angles to each other according to the state to which crystal **54** is switched. Analyzer **60** is then set to extinguish light passed by one or other of the two states of crystal **54** separated by domain wall **55.** Accordingly, by application of an appropriate voltage from source **58,** light from source **50** can be either passed or blocked by the optical system.

Because the zigzag walls of the present invention have a substantial width, they are employed in optical shutters wherein the optical aperture is large compared with the width of the wall. The increase in speed of operation compared with an ordinary planar domain wall is given by the expression $(Sz/Sp) = (m_z/mp) \cdot (w + A/A)$ where Sz/Sp is the ratio of switching speeds for a given field. m_z/mp is the ratio of mobilities for zigzag and planar walls. A is the width of the aperture and w is the width of the zigzag wall. As noted above, values of m_z/mp of about 30 are readily obtained, thus even where the aperture is equal to the width of the zigzag wall an increase in switching speed in optical switches of about 15 can be obtained by the use of the switching element of the present invention.

The existence of properties of zigzag domain walls depends on the ferroelastic properties of the material. Accordingly, the existence of ferroelectric properties coupled with the ferroelastic properties is not necessary in this invention. If coupled ferroelectric/ferroelastic crystals are employed, it is preferred that they should exhibit uniaxial behaviour. That is, the electric polarization must be constrained in one direction or the other along the specific axis. In addition to this, the twinning planes should have only a finite number of specific orientations within the crystal so that domain walls can be formed, capable of being moved in a controlled manner by external control of the electric field, or with mechanical stress. For the purposes of this invention, therefore, when ferroelastic/ferroelectric single crystals are employed, they should exhibit uniaxial electric polarization. Such crystals include all the crystals in the following Aizu point groups: 42mFmm2, 4F2, 222F2, 42mF2, 422F2, 622F2, 43mFmm2, and 23F2. Most preferred are crystals having the gadolinium molybdate structure, Aizu species 42mFmm2 which can be represented by the formula

$$(R_xR'_{1-x})_2O_3 \cdot 3Mo_{1-e}W_eO_3$$

Wherein R and R′ represent scandium, yttrium or a rare earth element having atomic number of from 57 to **71,** x from 0 to 1.0, and e is from 0 to 0.2. These crystals are described more fully in U. S. Pat. No. 3,437,432, issued to H. J. Borchardt on Apr. 8, 1969, and assigned to the assignee of the present invention.

More specifically it is the ferroelectric/ferroelastic phase commonly referred to as β' phase of the gadolinium molybate type materials which exhibits coupled ferroelectric/ferroelastic behaviour. These materials display two orientations of twinning planes which are normal to both two-fold orientation axes of the paraelectric group 42m. The electric polarization vector lies along the four-fold rotary inversion axis in the paraelectric phase in one or the other of the equivalent directions parallel thereto. These two directions are equivalent because they are interconverted by the two-fold rotation operations. Accordingly, these operations are lost to symmetry elements in going through the transition to the mm2 ferroelectric phase and they become the twinning operations that interconvert the ferroelectric/ferroelastic domains. In particular, crystals having the formula β'-$X_2(MlO_1)_3$ where X can be Md, Sm, Eu, Gd or Tb and the mixed rare earth molybdate $DyGd(MoO_4)_3$.

Mobile zigzag domain walls have also been observed in pure ferroelastic materials, i.e., materials in which the ferroelastic property is not coupled to another crystal property such as ferroelasticity. Thus α-lead phosphate is a pure ferroelastic material, Aizu species 3mF2/m, which has a Curie temperature of 179° above which the crystal point group is 3m and below which the crystal point group is 2/m. In the ferroelastic state a strain occurs in one of the three equivalent mirror planes of the prototype, high temperature trigonal phase resulting in one of three possible orientations for the monoclinic axis and thus three possible domains throughout which the monoclinic axis has the same orientation. Each pair of domains can interface at one of two possible, mutually perpendicular domain walls which lie along the direction of the domain interfaced. There are thus six possible domain walls which divide into two types: three n-walls oriented essentially perpendicular to the *bc* plane (corresponding to the *c* plane of the trigonal form) and oriented at 60° to the ac plane of each domain: and three t-walls each tilted at an angle of about 73° to the bc plane and oriented at 30° to the ac plane of each domain. The spontaneous strain appears as a "bend" α of about 4.4° across one *n* wall and a bend β of 1.6° in the plane perpendicular to the *n* wall in the bc plane. For a *t* wall the bend of the crystals across the wall is 4.6° and the bc planes of the domains are essentially colinear.

For a plate of α-lead phosphate in the ferroelastic state cut parallel to the bc plane at a thickness of 0.3 mm a mobile zigzag t wall has been observed with $p = 18\mu$ and w = 0.6 mm, i.e., having substantially the same dimensions as zigzag walls observed in various rare earth molybdate crystals.

α-lead phosphate is transparent from 0.28μ to 5μ. The refractive index is about 2.1, the material being biaxially birefringent $(-)\Delta n = 7 \times 10^{-3}$ in the bc plane and is thus suitable for the construction of mechanically actuated optical switches.

Since obvious modifications and equivalents in the invention will be evident to those skilled in the arts, I propose to be bound solely by the appended claims.

The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows:

1. A device comprising a crystal of a material having ferroelastic properties, said crystal having a domain wall extending across the crystal in a zigzag configuration and means to move said domain wall whereby a substantial portion of said crystal is switched from one ferroelastic strain state to a second ferroelastic strain state.

2. Device of claim **1** wherein said crystal is a crystal of a coupled ferroelectric/ferroelastic material exhibiting uniaxial electric polarization.

3. Device of claim **2** wherein said means to move the domain wall comprises electrodes on the faces of said crystal intersecting the ferroelectric axis and means to apply a voltage to said electrodes.

4. Device of claim **2** wherein said crystal is a crystal having the formula

$$(RR'_{1}{}^{-}{}_{x})_2O_3 \cdot 3Mo_{1-e}W_eO_3,$$

wherein R and R' are scandium, yttrium or a rare earth element having an atomic number of from 57 to 71, x is from 0 to 1.0 and e is from 0 0.2, and having the β'-gadolinium molybdate stucture.

5. Device of claim **4** wehrein said crystal is cut with faces perpendicular to the c-axis.

6. Device of claim **5** wherein said means to move the domain wall comprises electrodes on the faces perpendicular to the c-axis and means to apply an electric voltage to said electrodes.

7. An optical shutter comprising a transparent birefringent crystal of a material having ferroelastic properties, said crystal being divided into a first ferroelastic domain and a second ferroelastic domain by a domain wall extending in a zigzag configuration across said crystal,

means to move said domain wall across a substantial portion of said crystal whereby said portion is switched to the other domain, and

polarizing means on one side of said crystal and analyzing means on the other side of said crystal arranged to extinguish light transmitted through the assembly of said polarizer, said crystal and said analyzer when said first domain is in the opticl path.

8. The optical shutter of claim **7** wherein the aperture is large compared with the width of the domain wall.

9. The optical shutter of claim **8** wherein said crystal has the formula

$$(RR'_{1-x})_2O_3 \cdot 3Mo_{1-e}W_eO_3,$$

wherein R and R' are scandium, yttrium or a rare earth element having an atomic number from 57 to 71, x is from 0 to 1.0, and e is from 0 to 0.2; and having the β'-gadolinium molybdate structure, said crystal being cut as a plate with faces perpendicular to the c-axis.

10. Apparatus of claim **7** wherein said plate is cut on a λ/4 plate and said analyzer is a circular analyzer.

* * * * *

UNITED STATES PATENT OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 3,799,648

DATED : March 26, 1974

INVENTOR(S) : Richard B. Flippen

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Cover page, References Cited "Barkely" should be --Barkley--.

Col. 3, line 8 "one" should be --once--.

Col. 3, lines 21, 23, 39, and 56 each instance "microphotograph" should be --photomicrograph--.

Col. 4, line 10 "planes" should be --plane--.

Col. 4, line 26 between "angles" and "from" insert --θ--.

Col. 4, line 30 between "relation" and "tan" delete --to--.

Col. 4, line 34 delete "in Fig. 4" and replace with --there--.

Col. 5, line 32 "levels" should be --level--.

Col. 5, line 41 after "251,055" insert --,now U.S. 3,732,549.--.

Col. 5, line 66 second "the" should be --their--.

Col. 6, line 9 between "gadolinium" and "dysprosium" insert --and--.

Col. 6, line 20 "im" should be --in--.

Col. 6, line 21 "15" should not be in bold face type.

Col. 6, line 38 "cam" should be --can--.

UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 3,799,648

DATED : March 26, 1974

Page 2

INVENTOR(S) : Richard B. Flippen

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Col. 6, lines 46 and 47 "planar" should be --plane of the--.

Col. 7, lines 28 and 29 "(Sz/Sp) = (m_z/mp) · (w + A/A)" should read

-- $\frac{S_z}{S_p} = \frac{m_z}{m_p} \Big/ \frac{W + A}{A}$ --.

Col. 7, line 29 "Sz/Sp" should read -- $\frac{S_z}{S_p}$ --.

Col. 7, lines 30 and 33 each instance "$\frac{m_z}{mp}$" should be -- $\frac{m_z}{m_p}$ --.

Col. 7, line 36 between "15" and "can" insert --times--.

Col. 7, lines 55 and 56 change "42mFmm2, 4F2, 222F2, 42mF2, 422F2, 622F2, 43mFmm2" to read --$\bar{4}$2mFmm2, $\bar{4}$F2, 222F2, $\bar{4}$2mF2, 422F2, 622F2, $\bar{4}$3mFmm2--.

Col. 7, line 58 change "42mFmm2" to read --$\bar{4}$2mFmm2--.

Col. 7, line 64 between "x" and "from" insert --is--.

Col. 8, line 2 after "phase" (each occurrence) insert --,--.

Col. 8, line 7 insert a bar so "42m" should be --$\bar{4}$2m--.

UNITED STATES PATENT OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 3,799,648

DATED : March 26, 1974

INVENTOR(S) : Richard B. Flippen

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Col. 8, line 14 the 2 in "mm2" should not be in bold face type.

Col. 8, line 17 "$\beta'-X_2(M1O_1)_3$" should be --$\beta'-X_2(MoO_4)_3$--.

Col. 8, line 18 "Md" should be --Nd--.

Col. 8, line 23 "ferroelasticity" should be --ferroelectricity--.

Col. 8, lines 25 and 26 insert a bar over each 3 ($\bar{3}$).

Claim 4, Col. 9, line 15 formula should read --$(R_xR'_{1-x})_2O_3 \cdot 3Mo_{1-e}W_eO_3$--.

Claim 4, Col. 9, line 18 between "0" and "0.2" insert --to--.

Claim 9, Col. 10, line 17 the formula should read --$(R_xR'_{1-x})_2O_3 \cdot 3Mo_{1-e}W_eO_3$--.

Claim 10, Col. 10, line 25 "7" should be --9--.

UNITED STATES PATENT OFFICE

CERTIFICATE OF CORRECTION

Patent No. 3,799,648 Dated March 26, 1974

Inventor(s) Richard B. Flippen Page - 4

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

FIGURES 3 and 5b, should appear as shown below:

FIG. 3

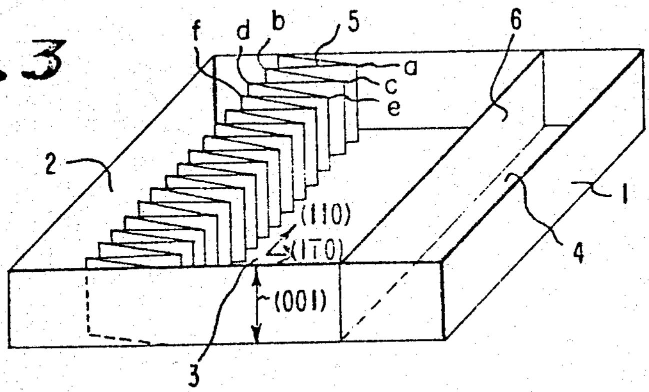
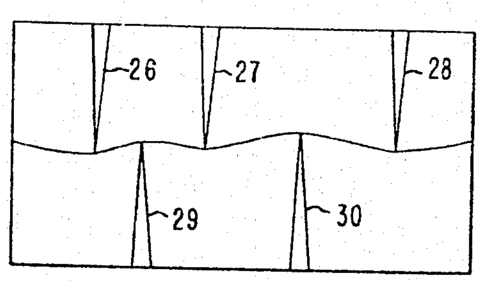


FIG. 5b



Signed and Sealed this

twenty-third Day of *September 1975*

[SEAL]

Attest:

RUTH C. MASON
Attesting Officer

C. MARSHALL DANN
Commissioner of Patents and Trademarks