

FIG. 1

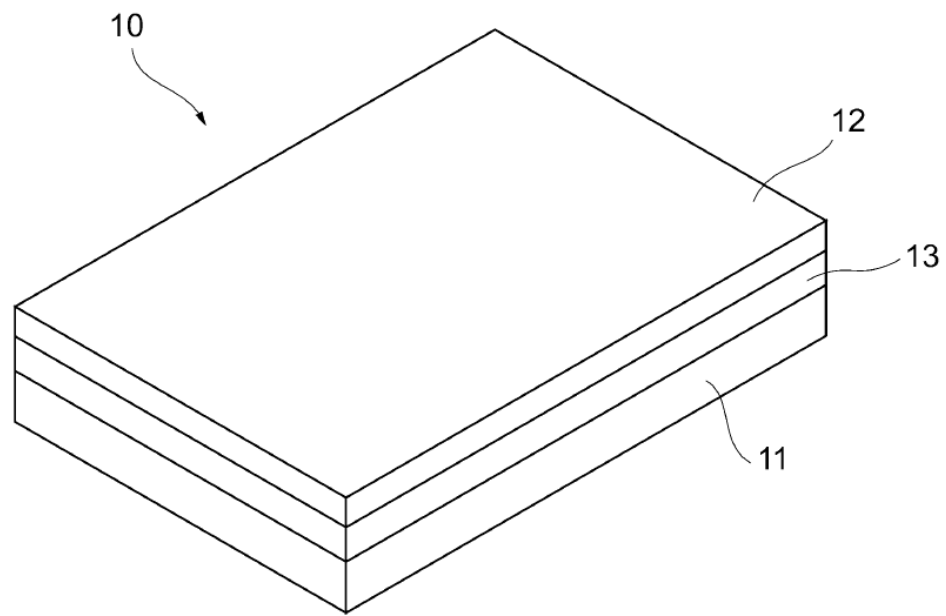


FIG. 2

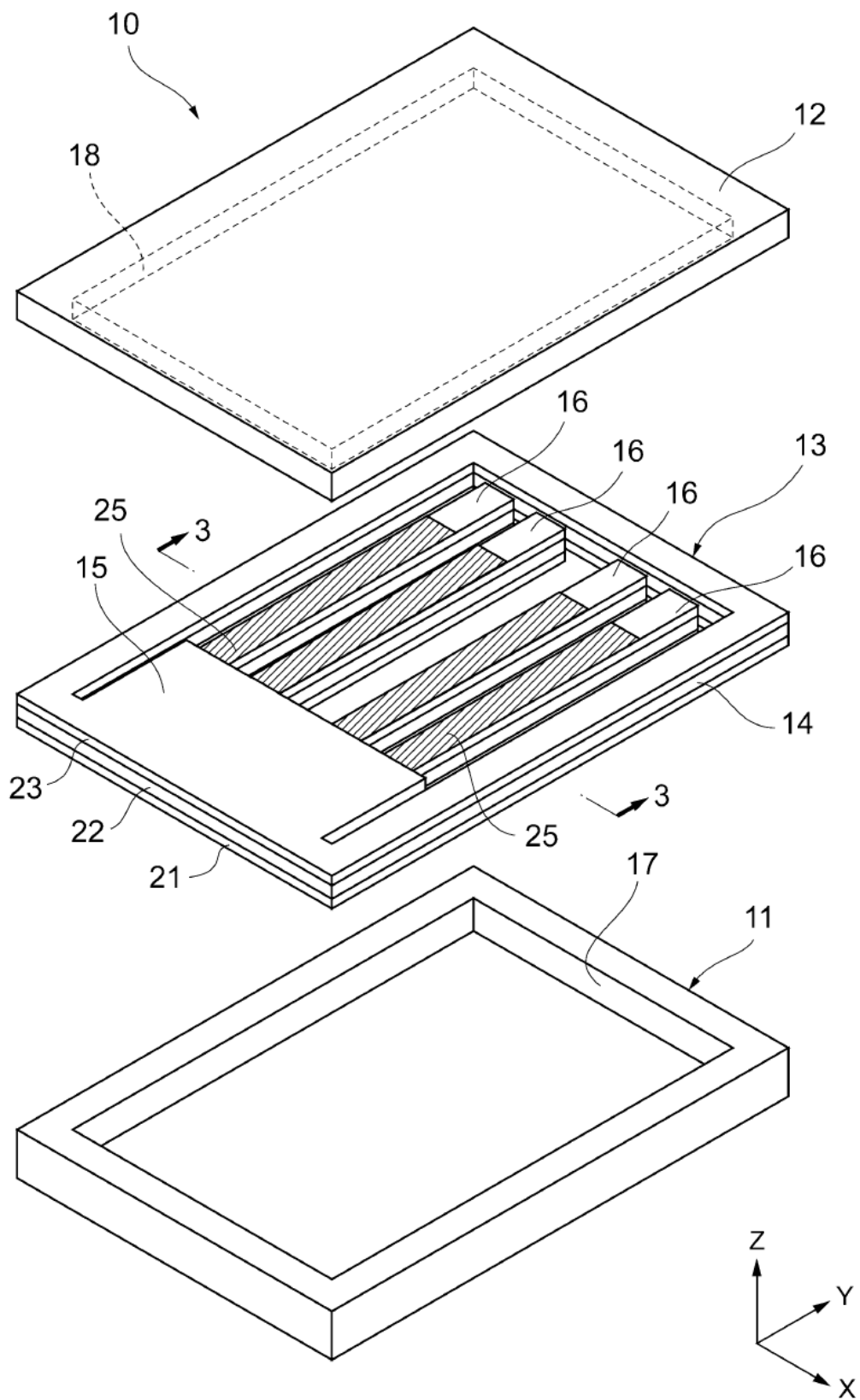


FIG. 3

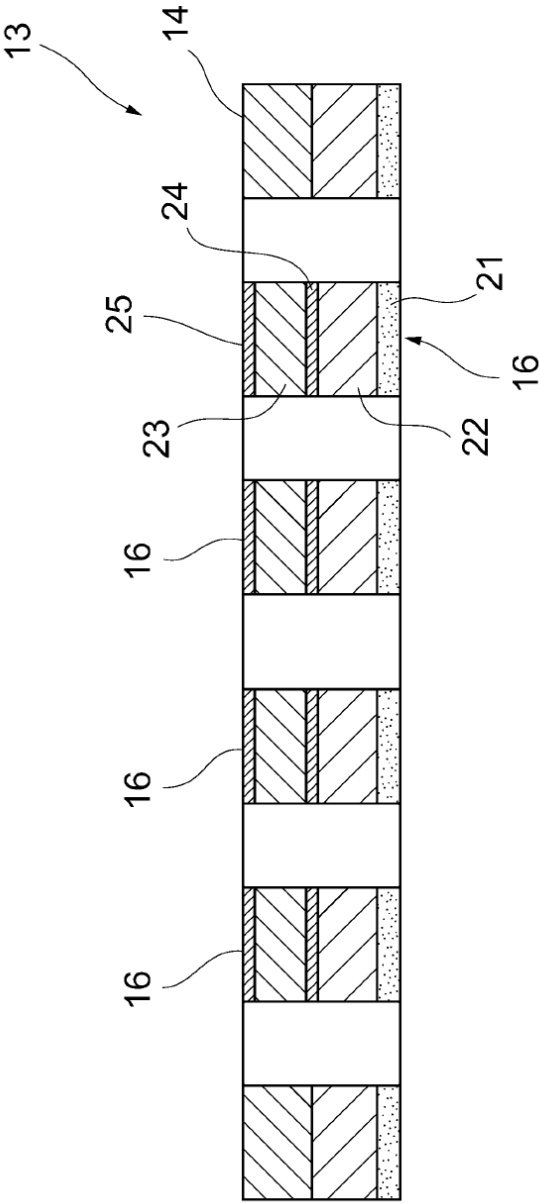


FIG. 4

| Ion | Valence | Coordination number | Ionic radius |
|-----|---------|---------------------|--------------|
| Al  | 3       | IV                  | 0.39         |
|     |         | V                   | 0.48         |
|     |         | VI                  | 0.535        |
| N   | -3      | IV                  | 1.46         |
|     | 3       | VI                  | 0.16         |
|     | 5       | III                 | -0.104       |
|     |         | VI                  | 0.13         |

| Ion | Valence | Coordination number | Ionic radius |
|-----|---------|---------------------|--------------|
| Ca  | 2       | VI                  | 1            |
|     |         | VII                 | 1.06         |
|     |         | VIII                | 1.12         |
|     |         | IX                  | 1.18         |
|     |         | X                   | 1.23         |
|     |         | XII                 | 1.34         |
| Hf  | 4       | IV                  | 0.58         |
|     |         | VI                  | 0.71         |
|     |         | VII                 | 0.76         |
|     |         | VIII                | 0.83         |
| Mg  | 2       | IV                  | 0.57         |
|     |         | V                   | 0.66         |
|     |         | VI                  | 0.72         |
|     |         | VIII                | 0.89         |
| Nb  | 3       | VI                  | 0.72         |
|     | 4       | VI                  | 0.68         |
|     |         | VIII                | 0.79         |
|     | 5       | IV                  | 0.48         |
|     |         | VI                  | 0.64         |
|     |         | VII                 | 0.69         |
|     |         | VIII                | 0.74         |
| Sc  | 3       | VI                  | 0.745        |
|     |         | VIII                | 0.87         |
| Sr  | 2       | VI                  | 1.18         |
|     |         | VII                 | 1.21         |
|     |         | VIII                | 1.26         |
|     |         | IX                  | 1.31         |
|     |         | X                   | 1.36         |
|     |         | XII                 | 1.44         |
| V   | 2       | VI                  | 0.79         |
|     | 3       | VI                  | 0.64         |
|     | 4       | V                   | 0.53         |
|     |         | VI                  | 0.58         |
|     |         | VIII                | 0.72         |
|     | 5       | IV                  | 0.355        |
|     |         | V                   | 0.46         |
|     |         | VI                  | 0.54         |
| Y   | 3       | VI                  | 0.9          |
|     |         | VII                 | 0.96         |
|     |         | VIII                | 1.019        |
|     |         | IX                  | 1.075        |
| Zn  | 2       | IV                  | 0.6          |
|     |         | V                   | 0.68         |
|     |         | VI                  | 0.74         |
|     |         | VIII                | 0.9          |
| Zr  | 4       | IV                  | 0.59         |
|     |         | V                   | 0.66         |
|     |         | VI                  | 0.72         |
|     |         | VII                 | 0.78         |
|     |         | VIII                | 0.84         |
|     |         | IX                  | 0.89         |

FIG. 5

| Ion | Valence | Coordination number | Ionic radius |
|-----|---------|---------------------|--------------|
| Cr  | 2       | VI                  | 0.8          |
|     |         |                     | 0.73         |
|     | 3       | VI                  | 0.615        |
|     | 4       | IV                  | 0.41         |
|     |         | VI                  | 0.55         |
|     | 5       | IV                  | 0.345        |
|     |         | VI                  | 0.49         |
|     |         | VIII                | 0.57         |
| 6   | IV      | 0.26                |              |
|     | VI      | 0.44                |              |
| Fe  | 2       | IV                  | 0.63         |
|     |         | IVSQ                | 0.64         |
|     |         | VI                  | 0.61         |
|     |         |                     | 0.78         |
|     |         | VIII                | 0.92         |
|     | 3       | IV                  | 0.49         |
|     |         | V                   | 0.58         |
|     |         | VI                  | 0.55         |
|     |         |                     | 0.645        |
|     |         | VIII                | 0.78         |
| 4   | VI      | 0.585               |              |
| 6   | IV      | 0.25                |              |
| Ni  | 2       | IV                  | 0.55         |
|     |         | IVSQ                | 0.49         |
|     |         | V                   | 0.63         |
|     |         | VI                  | 0.69         |
|     | 3       | VI                  | 0.6          |
|     |         |                     | 0.56         |
|     | 4       | VI                  | 0.48         |
| Ta  | 3       | VI                  | 0.72         |
|     | 4       | VI                  | 0.68         |
|     | 5       | VI                  | 0.64         |
|     |         | VII                 | 0.69         |
|     |         | VIII                | 0.74         |
| Ti  | 2       | VI                  | 0.86         |
|     | 3       | VI                  | 0.67         |
|     | 4       | IV                  | 0.42         |
|     |         | V                   | 0.51         |
|     |         | VI                  | 0.605        |
|     |         | VIII                | 0.74         |
| W   | 4       | VI                  | 0.66         |
|     | 5       | VI                  | 0.62         |
|     | 6       | IV                  | 0.42         |
|     |         | V                   | 0.51         |
|     |         | VI                  | 0.6          |

FIG. 6

|  | Sc<br>composition<br>ratio | Second<br>element | Second element<br>content (at%) | Valence<br>of second<br>element | Coordination<br>number of<br>second<br>element | Stress<br>(MPa) | Piezoelectric<br>constant $d_{33}$<br>(pC/N) |
|--|----------------------------|-------------------|---------------------------------|---------------------------------|------------------------------------------------|-----------------|----------------------------------------------|
|--|----------------------------|-------------------|---------------------------------|---------------------------------|------------------------------------------------|-----------------|----------------------------------------------|

|                          |      |   |   |   |   |       |      |
|--------------------------|------|---|---|---|---|-------|------|
| Comparative<br>Example 1 | 0.03 | - | - | - | - | -200  | 9.0  |
| Comparative<br>Example 2 | 0.05 | - | - | - | - | -225  | 11.0 |
| Comparative<br>Example 3 | 0.10 | - | - | - | - | -403  | 12.0 |
| Comparative<br>Example 4 | 0.20 | - | - | - | - | -560  | 13.0 |
| Comparative<br>Example 5 | 0.30 | - | - | - | - | -802  | 15.0 |
| Comparative<br>Example 6 | 0.40 | - | - | - | - | -1111 | 22.0 |
| Comparative<br>Example 7 | 0.50 | - | - | - | - | -1248 | 18.0 |
| Comparative<br>Example 8 | 0.55 | - | - | - | - | -1505 | 0.0  |

|                          |      |   |      |    |   |       |      |
|--------------------------|------|---|------|----|---|-------|------|
| Example 1                | 0.03 | W | 0.50 | 4+ | 6 | -155  | 9.2  |
| Example 2                | 0.05 | W | 0.50 | 4+ | 6 | -176  | 11.3 |
| Example 3                | 0.10 | W | 0.50 | 4+ | 6 | -342  | 12.2 |
| Example 4                | 0.20 | W | 0.50 | 4+ | 6 | -520  | 13.5 |
| Example 5                | 0.30 | W | 0.50 | 4+ | 6 | -765  | 15.4 |
| Example 6                | 0.40 | W | 0.50 | 4+ | 6 | -999  | 22.2 |
| Example 7                | 0.50 | W | 0.50 | 4+ | 6 | -1108 | 18.1 |
| Comparative<br>Example 9 | 0.55 | W | 0.50 | 4+ | 6 | -1342 | 0.0  |

|            |      |    |      |    |   |      |      |
|------------|------|----|------|----|---|------|------|
| Example 8  | 0.40 | Zr | 0.50 | 4+ | 6 | -985 | 22.2 |
| Example 9  | 0.40 | Ta | 0.50 | 3+ | 6 | -950 | 23.0 |
| Example 10 | 0.40 | Ti | 0.50 | 3+ | 6 | -947 | 23.1 |
| Example 11 | 0.40 | Cr | 0.50 | 3+ | 6 | -960 | 22.4 |
| Example 12 | 0.40 | Ni | 0.50 | 3+ | 6 | -951 | 23.4 |
| Example 13 | 0.40 | Fe | 0.50 | 3+ | 6 | -942 | 23.6 |

|            |      |    |       |    |   |       |      |
|------------|------|----|-------|----|---|-------|------|
| Example 14 | 0.40 | Fe | 0.005 | 3+ | 4 | -1090 | 24.0 |
| Example 15 | 0.40 | Fe | 0.01  | 3+ | 4 | -1074 | 24.2 |
| Example 16 | 0.40 | Fe | 0.10  | 3+ | 4 | -1001 | 24.3 |
| Example 17 | 0.40 | Fe | 0.20  | 3+ | 4 | -980  | 24.5 |
| Example 18 | 0.40 | Fe | 0.50  | 3+ | 4 | -900  | 24.5 |
| Example 19 | 0.40 | Fe | 0.70  | 3+ | 4 | -754  | 24.2 |
| Example 20 | 0.40 | Fe | 1.00  | 3+ | 4 | -642  | 24.1 |
| Example 21 | 0.40 | Fe | 1.10  | 3+ | 4 | -601  | 16.2 |

FIG. 7

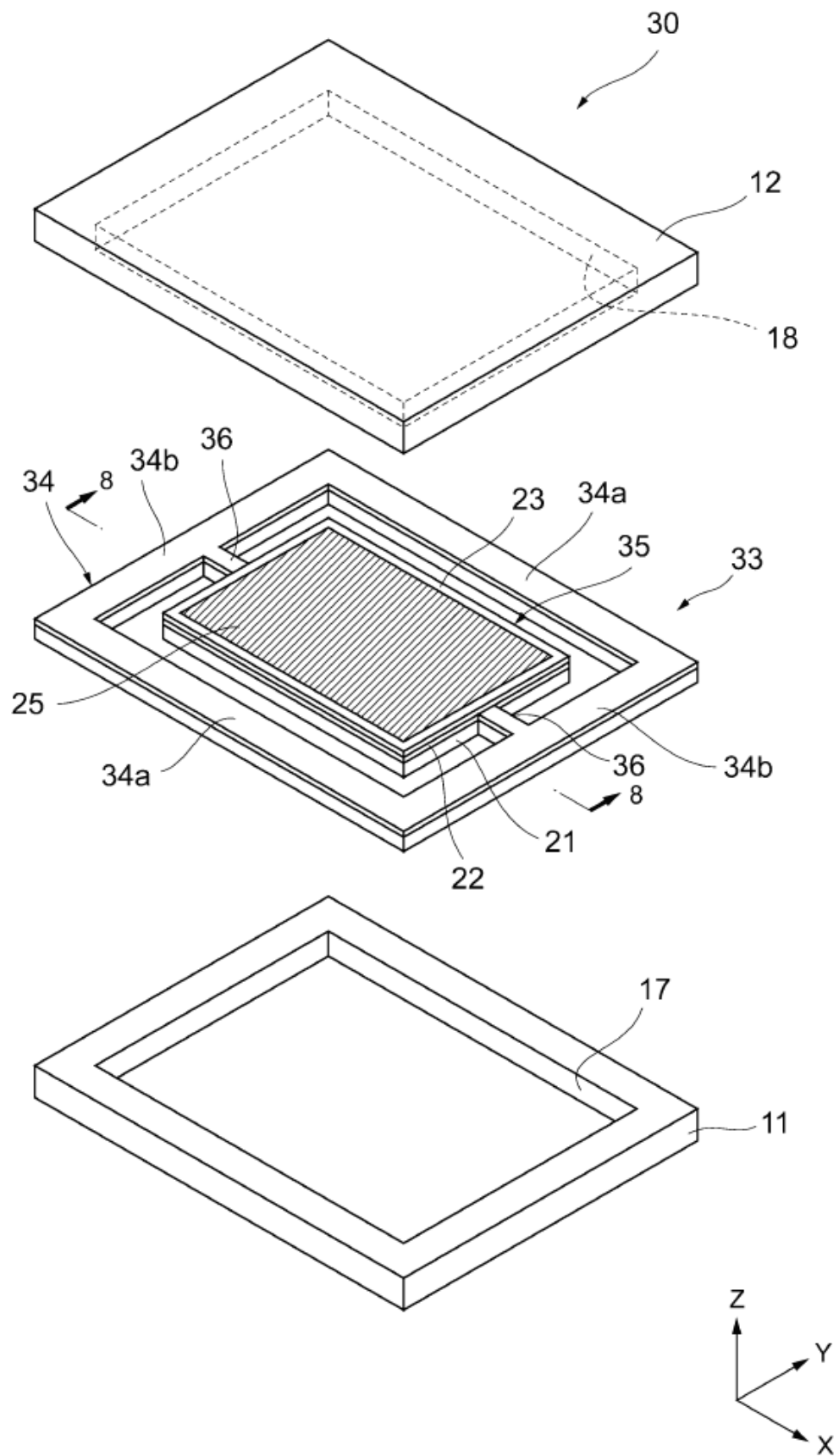


FIG. 8

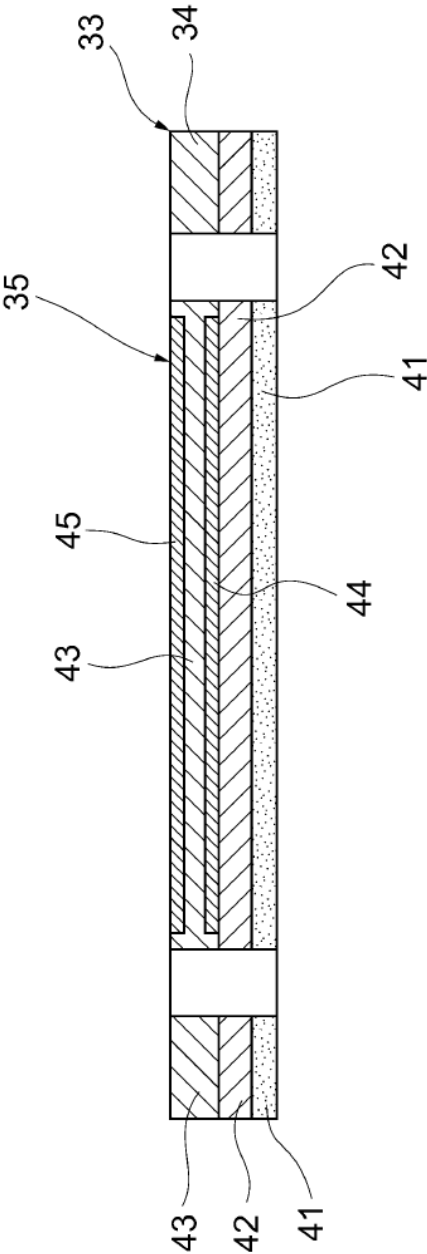


FIG. 9

|                          | First element        |                      | Second element | Second element content (at%) | Valence of second element | Coordination number of second element | Stress (MPa) | Piezoelectric constant $d_{33}$ (pC/N) |
|--------------------------|----------------------|----------------------|----------------|------------------------------|---------------------------|---------------------------------------|--------------|----------------------------------------|
|                          | Mg composition ratio | Nb composition ratio |                |                              |                           |                                       |              |                                        |
| Comparative Example 2-1  | 0.2                  | 0.2                  | Absent         | 0                            | -                         | -                                     | -750.6       | 18.2                                   |
| Experimental Example 2-1 | 0.2                  | 0.2                  | Fe             | 0.005                        | 3+                        | 4                                     | -719.4       | 18.0                                   |
| Experimental Example 2-2 | 0.2                  | 0.2                  | Fe             | 0.01                         | 3+                        | 4                                     | -708.8       | 18.1                                   |
| Experimental Example 2-3 | 0.2                  | 0.2                  | Fe             | 0.10                         | 3+                        | 4                                     | -660.7       | 18.0                                   |
| Experimental Example 2-4 | 0.2                  | 0.2                  | Fe             | 0.20                         | 3+                        | 4                                     | -646.8       | 17.9                                   |
| Experimental Example 2-5 | 0.2                  | 0.2                  | Fe             | 0.50                         | 3+                        | 4                                     | -605.0       | 17.9                                   |
| Experimental Example 2-6 | 0.2                  | 0.2                  | Fe             | 0.70                         | 3+                        | 4                                     | -506.0       | 18.1                                   |
| Experimental Example 2-7 | 0.2                  | 0.2                  | Fe             | 1.00                         | 3+                        | 4                                     | -423.7       | 17.6                                   |
| Experimental Example 2-8 | 0.2                  | 0.2                  | Fe             | 1.10                         | 3+                        | 4                                     | -396.7       | 10.5                                   |

FIG.10

|                          | First element        |                      | Second element | Second element content (at%) | Valence of second element | Coordination number of second element | Stress (MPa) | Piezoelectric constant $d_{33}$ (pC/N) |
|--------------------------|----------------------|----------------------|----------------|------------------------------|---------------------------|---------------------------------------|--------------|----------------------------------------|
|                          | Mg composition ratio | Hf composition ratio |                |                              |                           |                                       |              |                                        |
| Comparative Example 3-1  | 0.25                 | 0.25                 | Absent         | 0                            | -                         | -                                     | -1206.6      | 19.0                                   |
| Experimental Example 3-1 | 0.25                 | 0.25                 | Fe             | 0.005                        | 3+                        | 4                                     | -1144.5      | 19.2                                   |
| Experimental Example 3-2 | 0.25                 | 0.25                 | Fe             | 0.01                         | 3+                        | 4                                     | -1117.0      | 19.1                                   |
| Experimental Example 3-3 | 0.25                 | 0.25                 | Fe             | 0.10                         | 3+                        | 4                                     | -1081.1      | 18.9                                   |
| Experimental Example 3-4 | 0.25                 | 0.25                 | Fe             | 0.20                         | 3+                        | 4                                     | -960.4       | 19.0                                   |
| Experimental Example 3-5 | 0.25                 | 0.25                 | Fe             | 0.50                         | 3+                        | 4                                     | -891.0       | 18.6                                   |
| Experimental Example 3-6 | 0.25                 | 0.25                 | Fe             | 0.70                         | 3+                        | 4                                     | -754.0       | 18.8                                   |
| Experimental Example 3-7 | 0.25                 | 0.25                 | Fe             | 1.00                         | 3+                        | 4                                     | -706.2       | 19.0                                   |
| Experimental Example 3-8 | 0.25                 | 0.25                 | Fe             | 1.10                         | 3+                        | 4                                     | -589.0       | 13.2                                   |