field (e.g., V^{5+} in ZnO). A similar effect may apply to Ta^{5+} in AlN because of large lattice expansion. Ta^{5+} is not expected to be that much smaller than Al^{3+} so it is uncertain why there is an increase in the d_{33} piezoelectric coefficient. This is possibly associated with charge compensating defects.

In some examples, AlN may be doped with oxygen. For example, oxygen may be present in sputtering gas used during deposition of AlN-based films. Despite the increasing ionicity of oxygen, the magnitude of the piezoelectric coefficient of oxygen-doped AlN does not increase. Without being bound to a particular theory, it is possible that oxygen defects in AlN may be compensated by aluminum vacancies ($\square_{Al}$). Further, the presence of oxygen in AlN may cause second phase Al_2O_3 to form. It thus may be difficult to control the anion stoichiometry. Accordingly, in doped AlN, it may be preferable to avoid anion mixing, but rather to make all adjustments on a cation basis.

The addition of dopants into AlN may cause one or more of a number of types of crystallographic defects. One type of defect involves electronic substitutions. For example, Si substituted for Al in AlN may act as a deep level donor (320 meV) which may reduce the conductivity of the material, while C substituted for Al in AlN may act as a deep level acceptor (500 meV). Point defects include vacancies, interstitials, and anti-site defects. In AlN, vacancies are more energetically favorable than interstitials or anti-site defects. For Al vacancies atomic displacement away from the vacancy is observed. For N vacancies atomic displacement toward the vacancy is observed. Stacking faults in AlN include {1120} stacking fault configurations. Stacking faults may be a preferred region for substitutional ions or Al vacancies. Systematic vacancies may be caused by substitution of Al in AlN by some elements. For example, Ta^{5+} and Zr^{4+} doping of AlN would be compensated for by native defects such as Al vacancies (V_{Al} or $\square_{Al}$). Smaller ions than Al^{3+} or Ta^{5+} may form elastically driven defect couples with $2\square_{Al} - 3Ta_{Al}$. The $\square_{Al}$ and Ta_{Al} vacancies or substitutions may expand nearest neighbor N tetrahedral. Si^{4+} may contract nearest neighbor N tetrahedral forming defect couples with V_{Al}.

SUMMARY

In a first aspect, the present disclosure provides a piezoelectric material comprising: AlN doped with cations of one or more elements selected from the group consisting of: a) one of Sb, Ta, Nb, or Ge; b) Cr in combination with one or more of B, Sc, Y, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, or Yb; c) one of Nb and Ta in combination with one of Li, Mg, Ca, Ni, Co, and Zn; d) Ca in

combination with one of Si, Ge, Ti, Zr, and Hf; e) Mg

in combination with one of Si, Ge, and Ti; and f) one or more of Co, Sb, Ta, Nb, Si, or Ge in combination with one or more of Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, or Yb; the cations at least partially substitute for Al in the crystal structure of the piezoelectric material.

In a second aspect, the present disclosure provides an acoustic wave resonator including the piezoelectric material according to the first aspect.

In a third aspect, the present disclosure provides a filter including the acoustic wave resonator according to the second aspect.

In a fourth aspect, the present disclosure provides an electronic device module including the filter according to the third aspect.

In a fifth aspect, the present disclosure provides an electronic device including the electronic device module according to the fourth aspect.

In some embodiments, the piezoelectric material has one of the formulas $Al_{1-x}Ge_{3/4x}\square 1/4xN$ or $Al_{1-5/3x}Ta^{5+}_{x}\square 2/3xN$, $\square$ representing a vacancy in an Al site in the crystal structure of the piezoelectric material, $0 < x < 0.25$.

In some embodiments, the piezoelectric material has the formula $Al_{1-2x}B_xCr_xN$ $0<x<0.15$.

In some embodiments, the piezoelectric material has the formula $Al_{1-5/3x-3y}Mg_{2y}Ta_{x+y}\square_{2/3x}N$, $\square$ representing a vacancy in an Al site in the crystal structure of the piezoelectric material, $1 > 5/3x + 3y$, $0 < x < 0.3$, $0 < y < 0.25$.

In some embodiments, the piezoelectric material has the formula $Al_{1-2x}Mg_xSi_xN$ $0<x<0.15$.

In some embodiments, the piezoelectric material has the formula $Al_{1-x-y}Cr^{3+}_{x}M^{III}_{y}N$, $M^{III}= Sc^{3+}$, Y^{3+}, $Sm^{3+}...Yb^{3+}$, $Sm^{3+}...Yb^{3+}$ = any one or more of the Lanthanides with atomic numbers from 62-70.

The piezoelectric material may have a Wurtzite crystal structure.

In some embodiments, an acoustic wave resonator includes the piezoelectric material. The acoustic wave resonator may be configured as a solidly mounted resonator. The acoustic wave resonator may be configured as a film bulk acoustic resonator.

In some embodiments, a filter includes the acoustic wave resonator. The filter may have a passband in the radio frequency band.

In some embodiments, an electronic device module includes the filter.

In some embodiments, an electronic device includes the electronic device module. The electronic device module may be a radio frequency electronic device module.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a chart of impedance vs. frequency for an example of an acoustic wave filter.

FIG. 2 is a chart illustrating the dielectric polarizabilities of various trivalent cations vs. crystal radius;

FIG. 3 is a table of selected material parameters of various electromechanical materials;

FIG. 4 illustrates the Wurtzite crystallographic structure;