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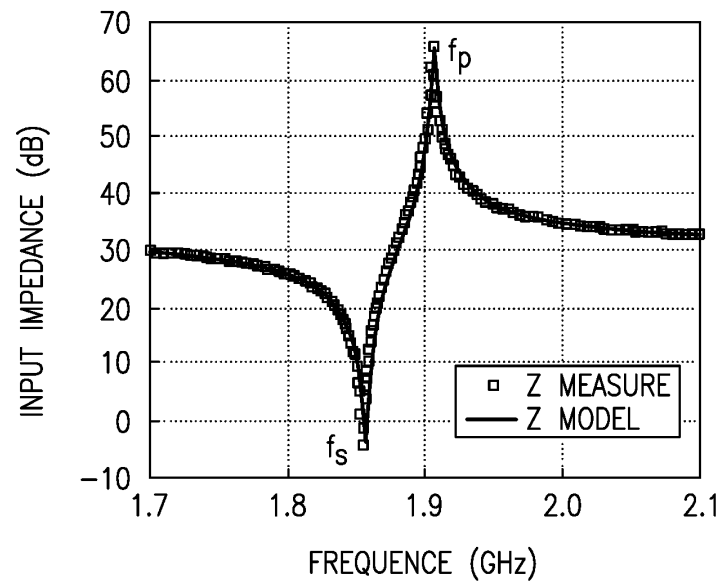


FIG.1

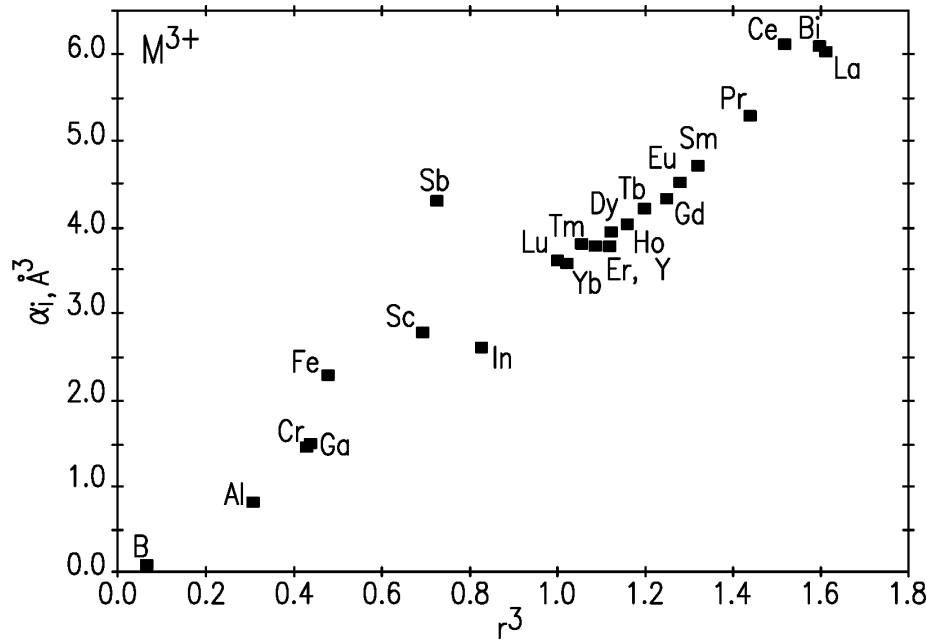


FIG.2

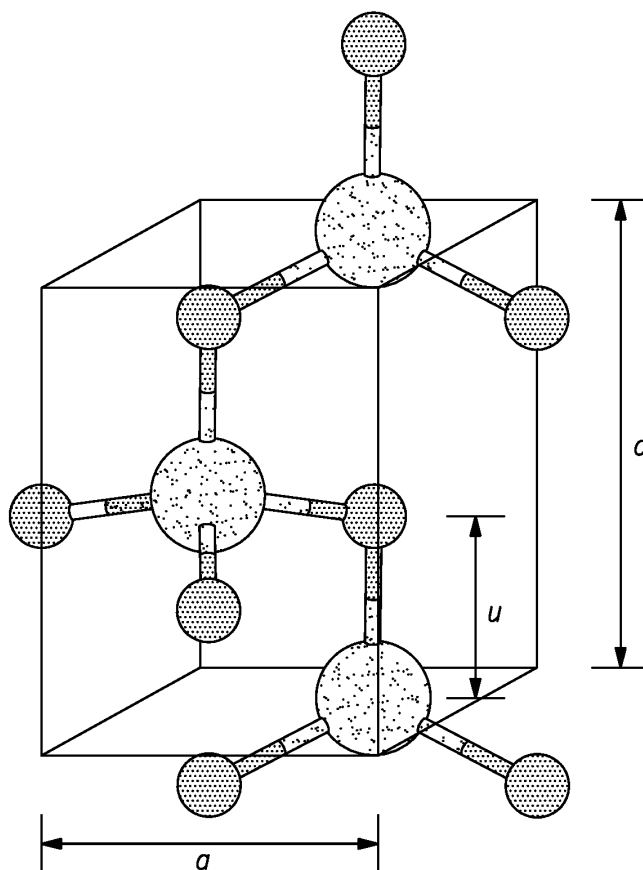
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Material	Elastic Modulus c_{33} (GPa)	Acoustic Velocity (m/s)	Piezoelectric Coefficient e_{33} (Cm ⁻²)	$f \times Q^*$ (Hz)	k_{eff}^2 (%)
Si	165	8415	N/A	2.5×10^{13}	N/A
SiC	605	13100	+0.2	3.5×10^{14}	0.08
GaAs	118	2470	-0.16	-- [†]	0.04
AlN	390	11000	+1.55	10^{13}	5.6
Sc doped AlN	244	8509	+3.9	3×10^{11}	15.5
LiNbO ₃ (X-cut, [‡])	60	3900	+3.65	7.7×10^{11} (measured)	16
GaN	398	8044	+0.65	2.5×10^{13} (theory) 5×10^{12} (measured)	2

* For anharmonic phonon scattering in Akhieser regime

[†] Data not available[‡] LiNbO₃ data are for shear mode, not longitudinal mode**FIG.3**

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**FIG.4**

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Calculated spontaneous polarization (in units of C/m^2), Born effective charges (in units of e), and piezoelectric constants (in units of C/m^2) for III–V wurtzite nitrides and II–VI wurtzite oxides. Theoretical results for ZnO and BeO are included.

	P^{eq}	Z^*	$du/d\epsilon_3$	e_{33}	e_{31}	$e_{33}^{(0)}$	$e_{31}^{(0)}$
AlN	−0.081	−2.70	−0.18	1.46	−0.60	−0.47	0.36
GaN	−0.029	−2.72	−0.16	0.73	−0.49	−0.84	0.45
InN	−0.032	−3.02	−0.20	0.97	−0.57	−0.88	0.45
ZnO	−0.057	−2.11	−0.21	0.89	−0.51	−0.66	0.38
BeO	−0.045	−1.85	−0.06	0.02	−0.02	−0.60	0.35
ZnO ^a	−0.05	−2.05	−0.25	1.21	−0.51	−0.58	0.37
BeO ^a	−0.05	−1.72	−0.09	0.50	—	−0.29	—

FIG.5A

Property	AlN	GaN	InN
Density (g/cc)	3.23	6.15	6.81
Transverse Sound Velocity (cm/s)	3.70×10^5	2.68×10^5	2.55×10^5
Longitudinal Sound Velocity (cm/s)	9.06×10^5	6.56×10^5	6.24×10^5
Static Dielectric Constant	8.5	8.9	15.3
High Frequency Dielectric Constant	4.77	5.35	8.4
Energy Gap (eV)	6.2	3.39	1.89
Piezoelectric Coefficient (e_{14})	0.92	0.375	0.375
Piezoelectric Coefficient (e_{33})	1.55		
Lattice Parameter a (angstroms)	3.11	3.189	3.54
Lattice Parameter c (angstroms)	4.98	5.185	5.70
c/a ratio	1.60	1.626	1.61

FIG.5B

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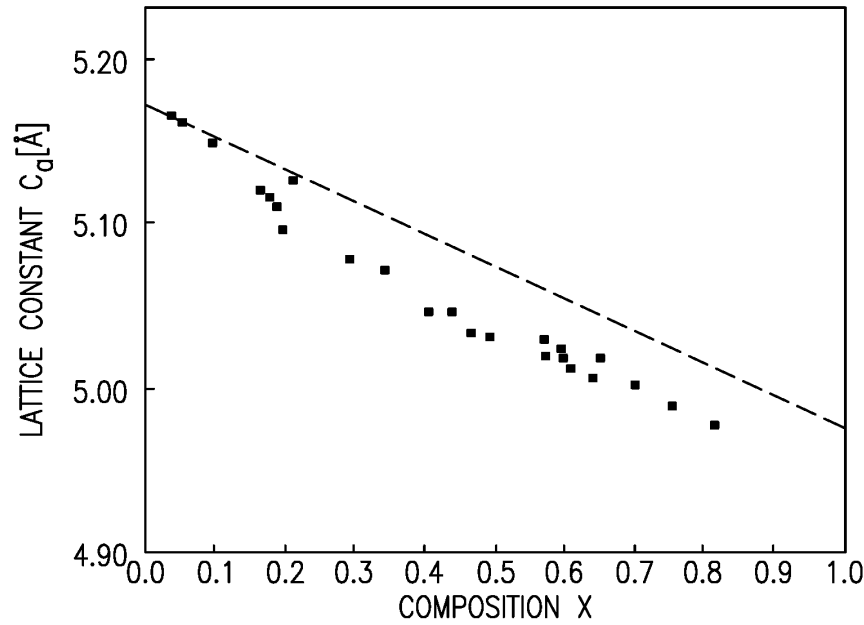


FIG.6A

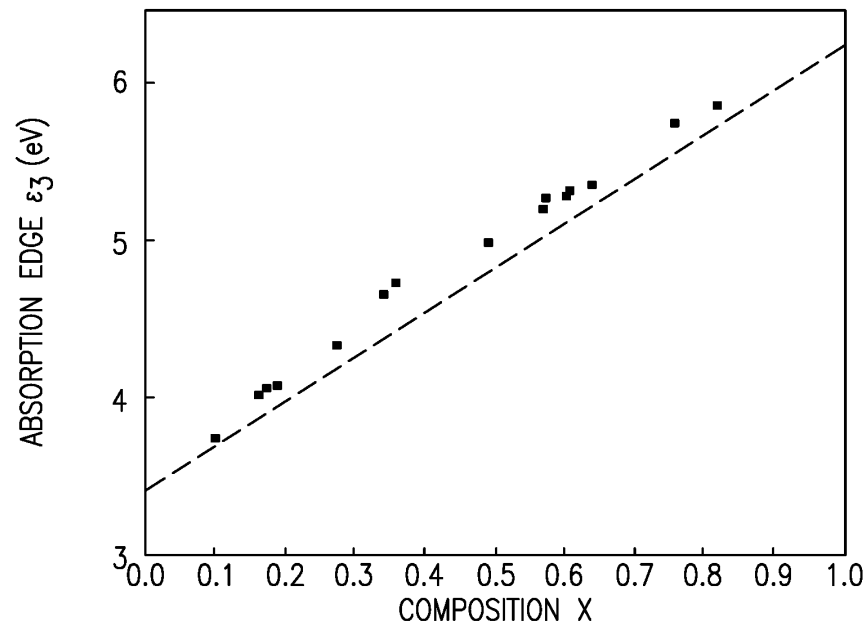


FIG.6B

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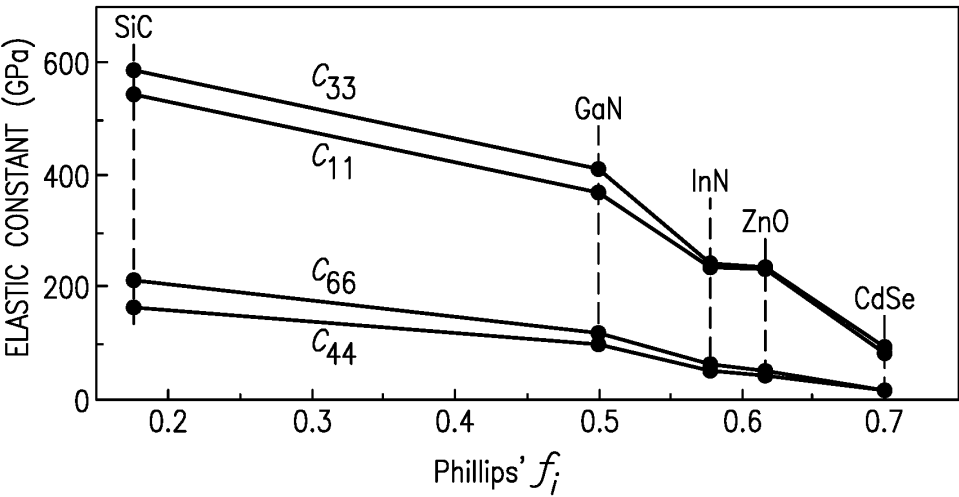


FIG.7A

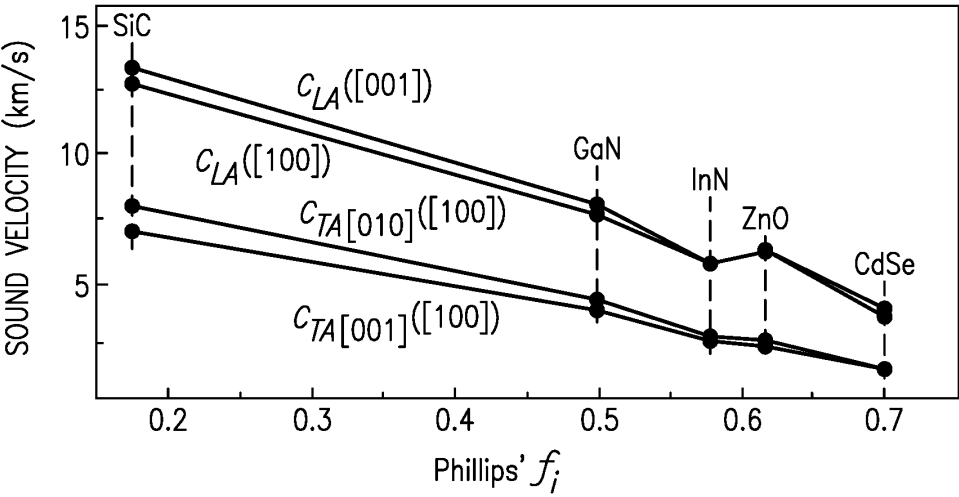


FIG.7B

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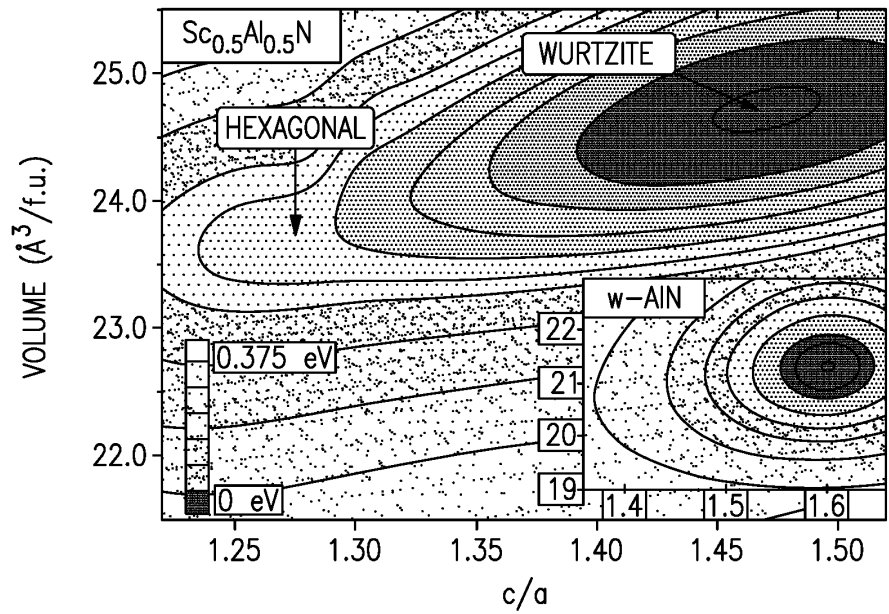


FIG.8A

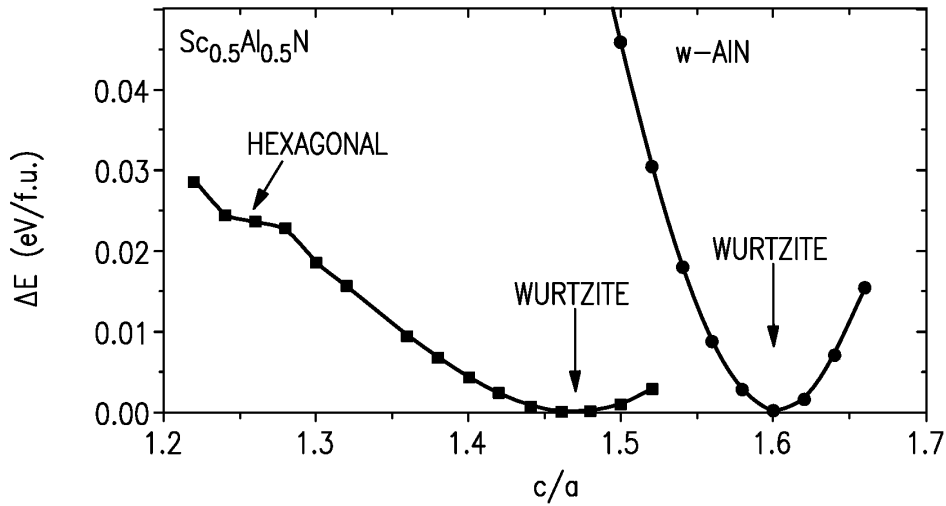


FIG.8B

Material	ρ (g/cc)	$v_s^d=(c_{33}^D/\rho)^{1/2}$ (m/s)	c_{33}^D (GPa)	c_{33}^E (GPa)	e_{33} (c/m ²)	d_{33} (pm/V)	ϵ' (50 kHz)	$d_{33f}=e_{33}/c_{33}^E$ (pm/V)	$k_t(\%)=[e_{33}^2/(c_{33}^D \epsilon_{33}^s)]^{1/2}$	Q	FOM ($k_t^2 \times Q$)
AlN	3.260	11350	420	395	1.55	5.5	10.2	3.9	6.0	4000	
ab initio Al _{0.88} Sc _{0.12} N				290	1.61		12.0				
experiment Al _{0.88} Sc _{0.12} N	3.255	10300	345	320	1.70		13.0	5.3	7.9 7.3 (BVD circuit)	>650	

FIG.8C

Material	$f_{s,m}$ (GHz)	$Q_{p,m}$	$Q_{B,m}$	$k^2_{eff,m}$ (%)	FOM $k^2_{eff,m} \times Q_{B,m}$	ϵ_r	E_{c33} (GPa)	e_{33} (C/m ²)	k_t^2
AlN	2.3605	739	790	5.50	40	10.1	370	1.48	6.16
Al _{0.97} Sc _{0.03} N	2.2935	601	730	6.89	50	10.9	346	1.66	7.55
Al _{0.91} Sc _{0.09} N	2.2339	513	690	9.50	65	12.4	326	1.94	9.53
Al _{0.85} Sc _{0.15} N	2.1522	348	410	12.07	60	14.1	270	2.14	12.00

FIG.8D

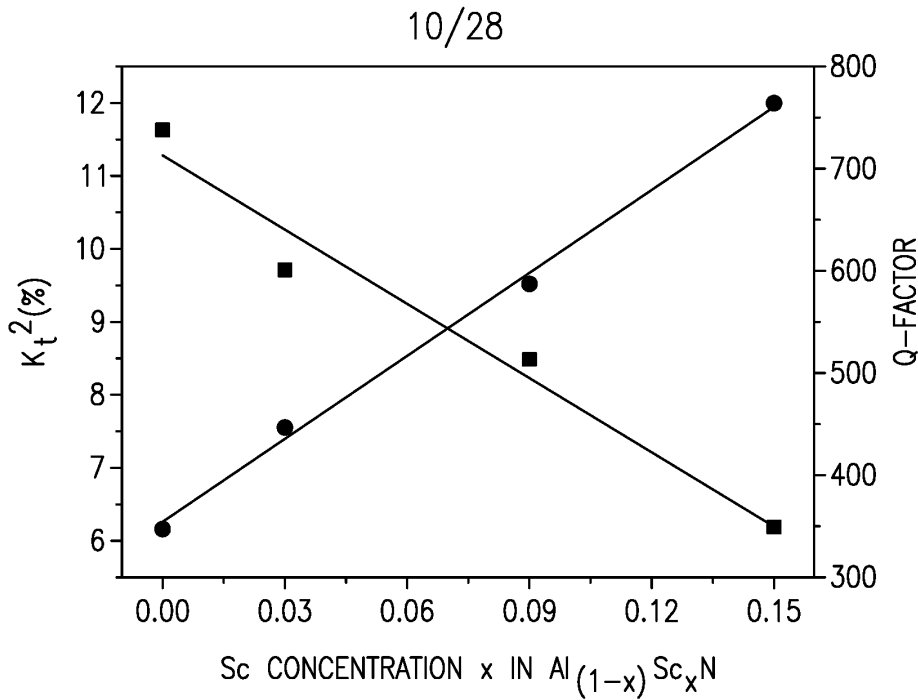


FIG.8E

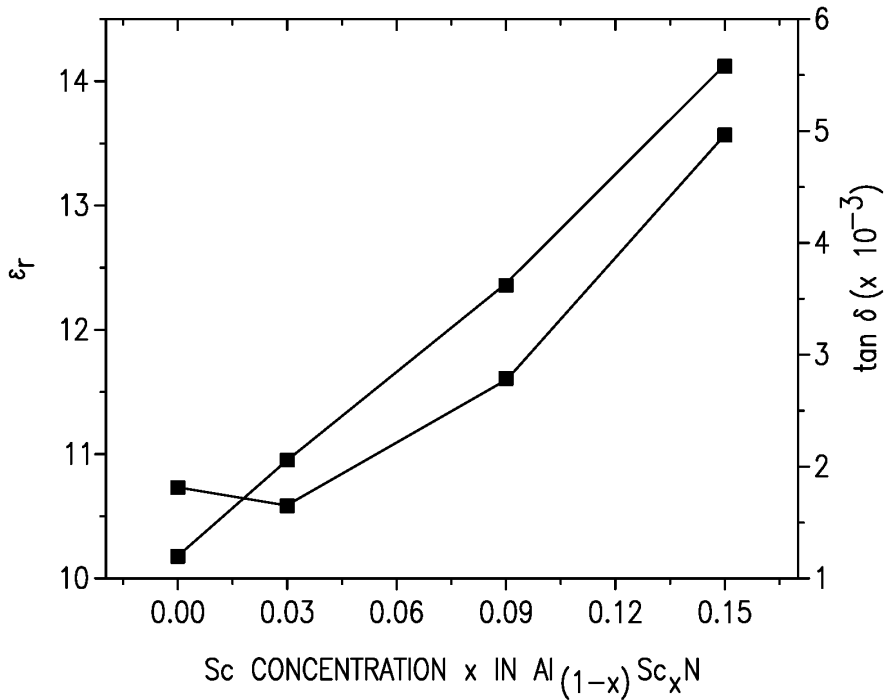


FIG.8F

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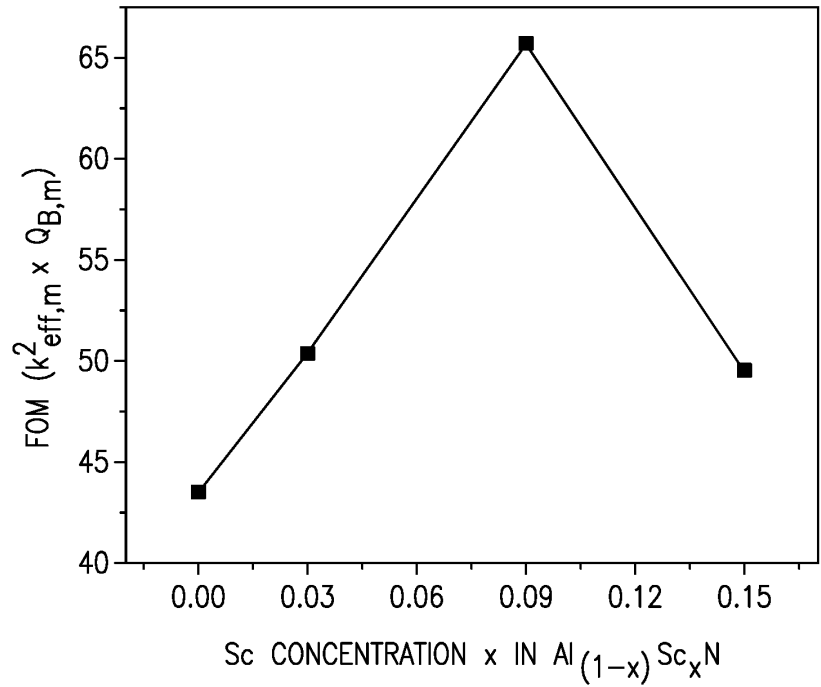


FIG.8G

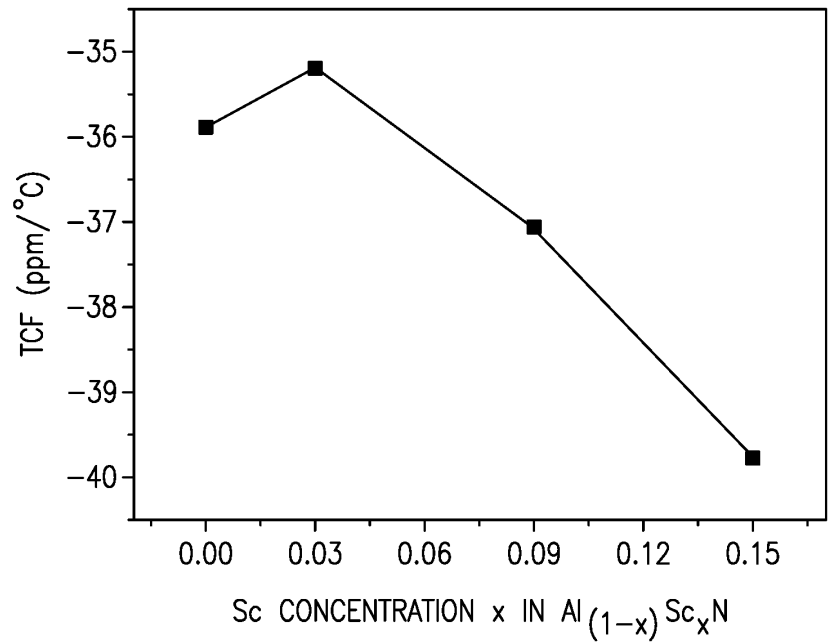


FIG.8H

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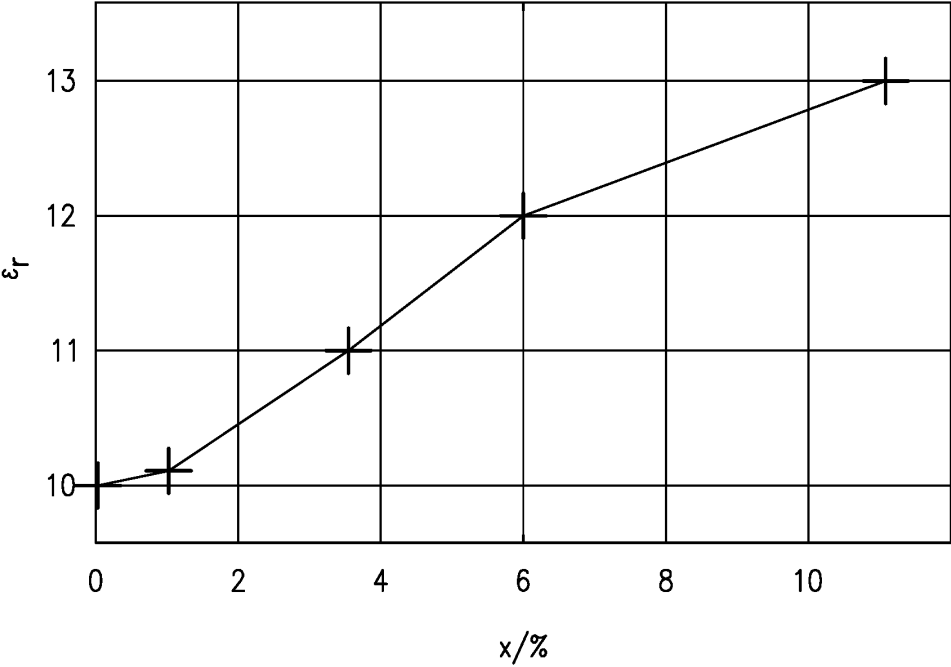


FIG.9A

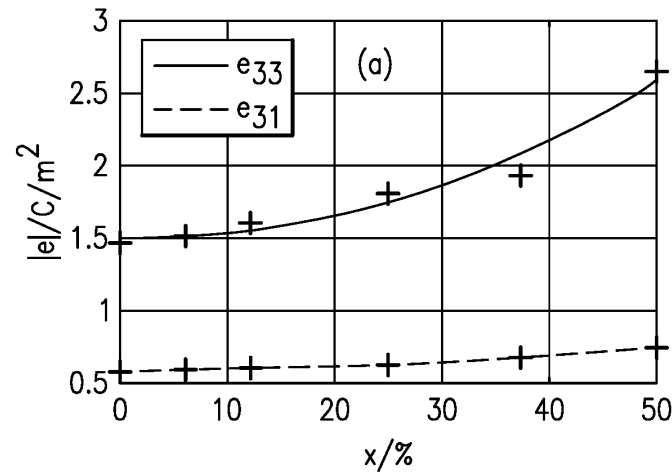
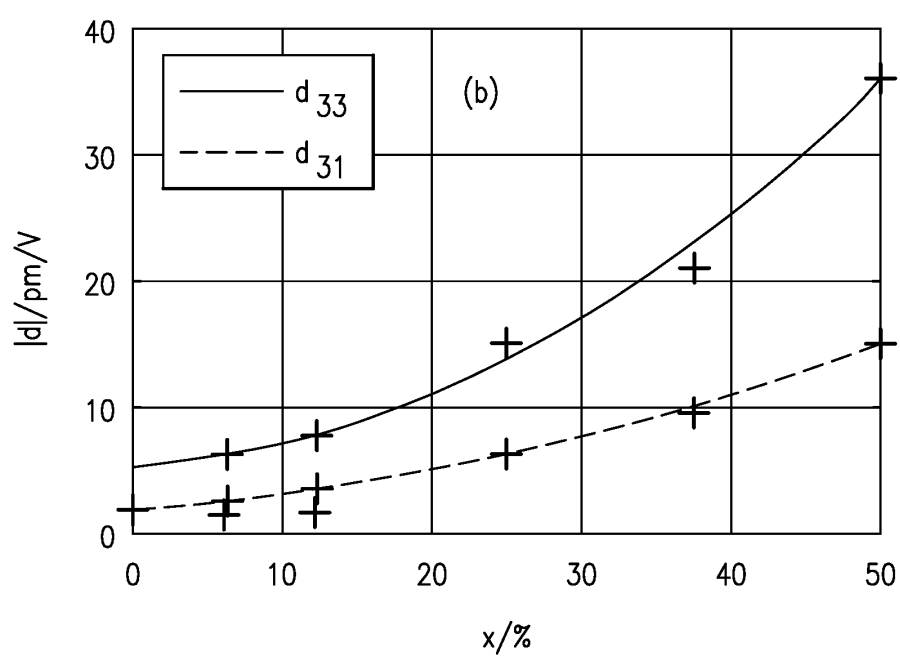


FIG.9B

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**FIG.9C**

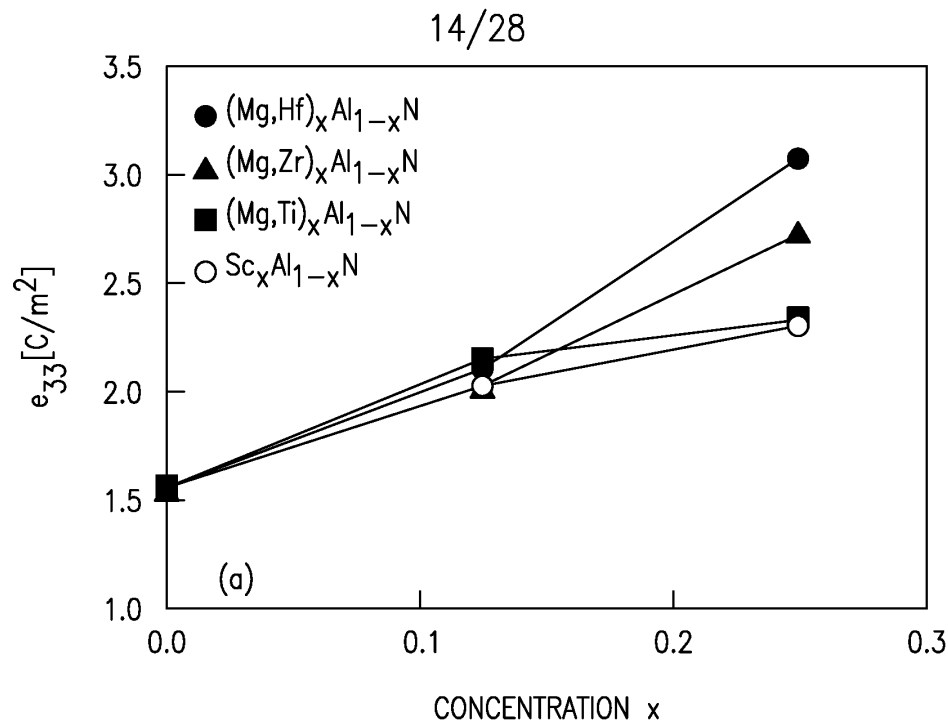


FIG.10A

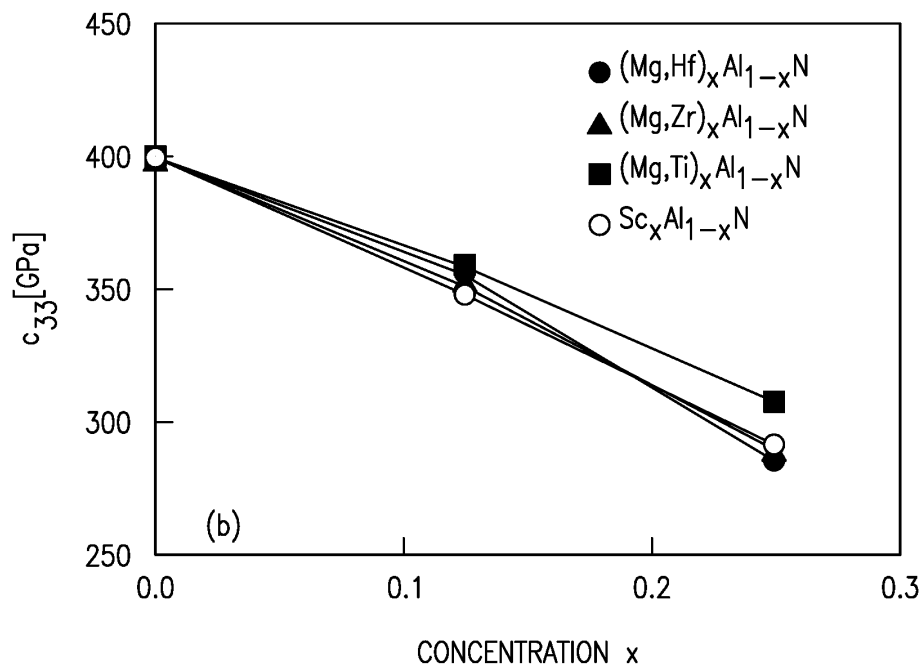


FIG.10B

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Material	ϵ_r	d_{33} (pC/N)	c_{33} (GPa)	Longitudinal Sound Velocity (m/sec)	Q_r	Q_d	k^2 (%)	FOM
AlN	10.0	7.0	395	10900	1053	1218	7.1	81
$(\text{Mg}_{0.5}\text{Zr}_{0.5})_{0.13}\text{Al}_{0.87}\text{N}$	13.6	10.4	315	9484	808	651	8.5	62
$(\text{Mg}_{0.5}\text{Hf}_{0.5})_{0.13}\text{Al}_{0.87}\text{N}$	13.3	10.5	336	9214	781	539	10.0	65

FIG.10C

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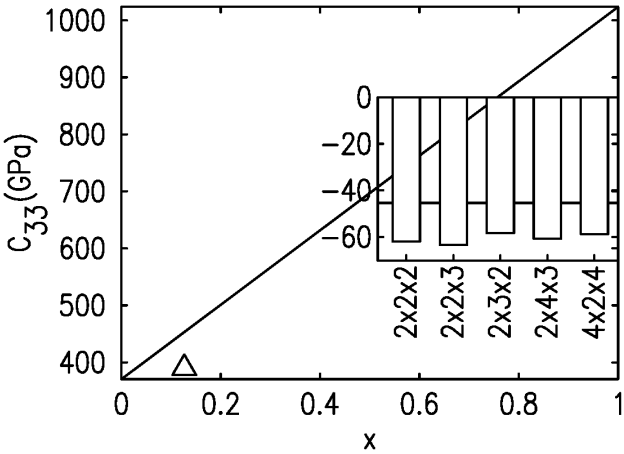


FIG. 11A

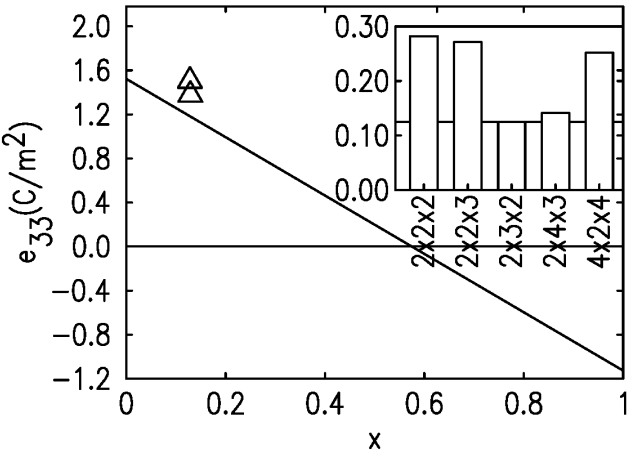


FIG. 11B

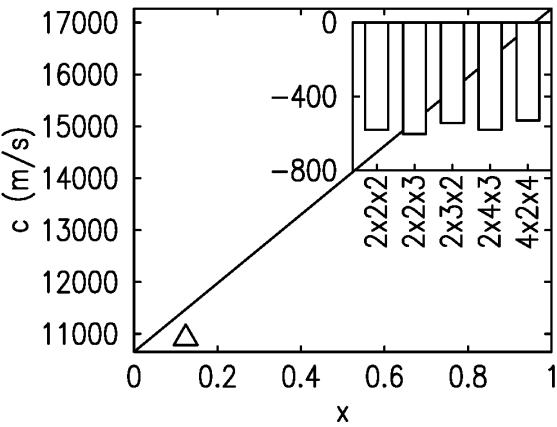


FIG. 11C

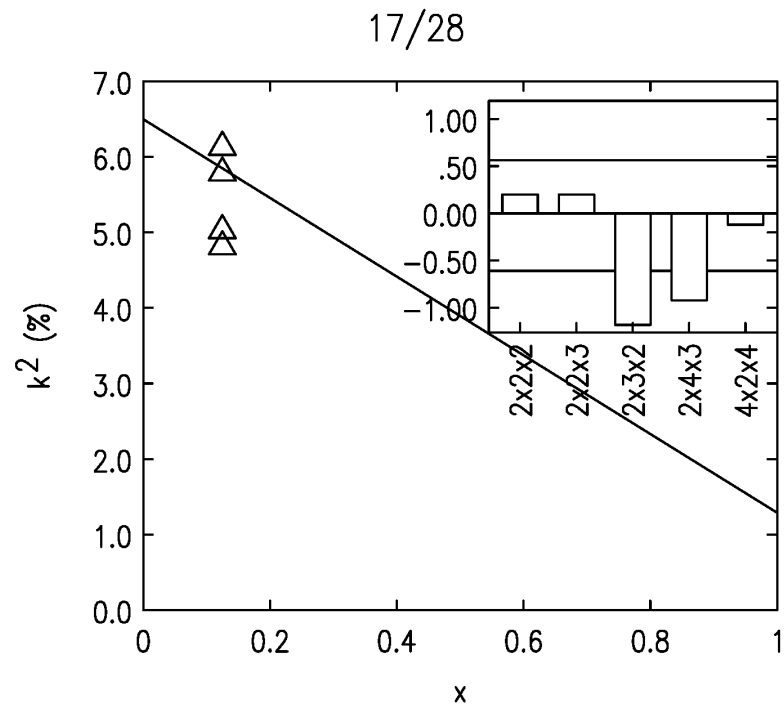


FIG.11D

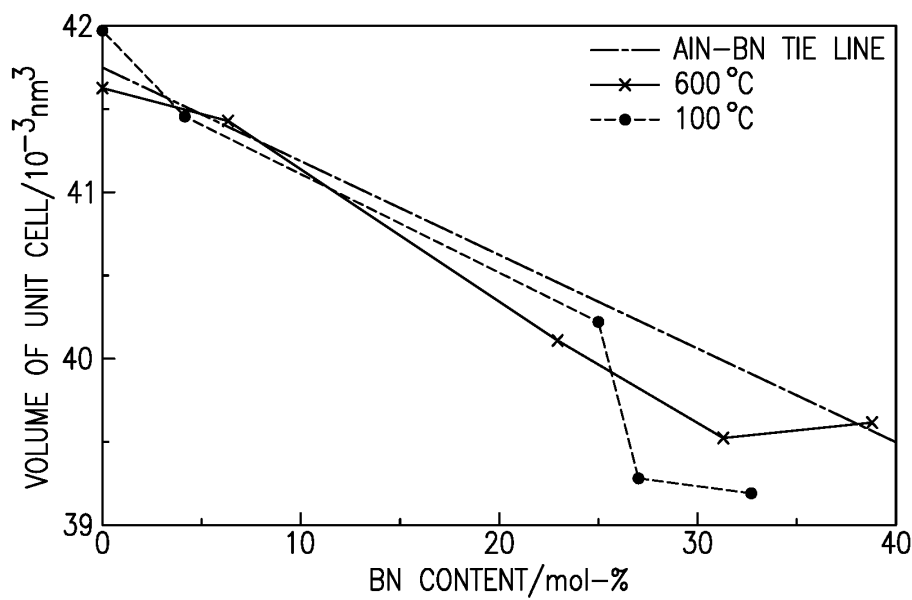


FIG.11E

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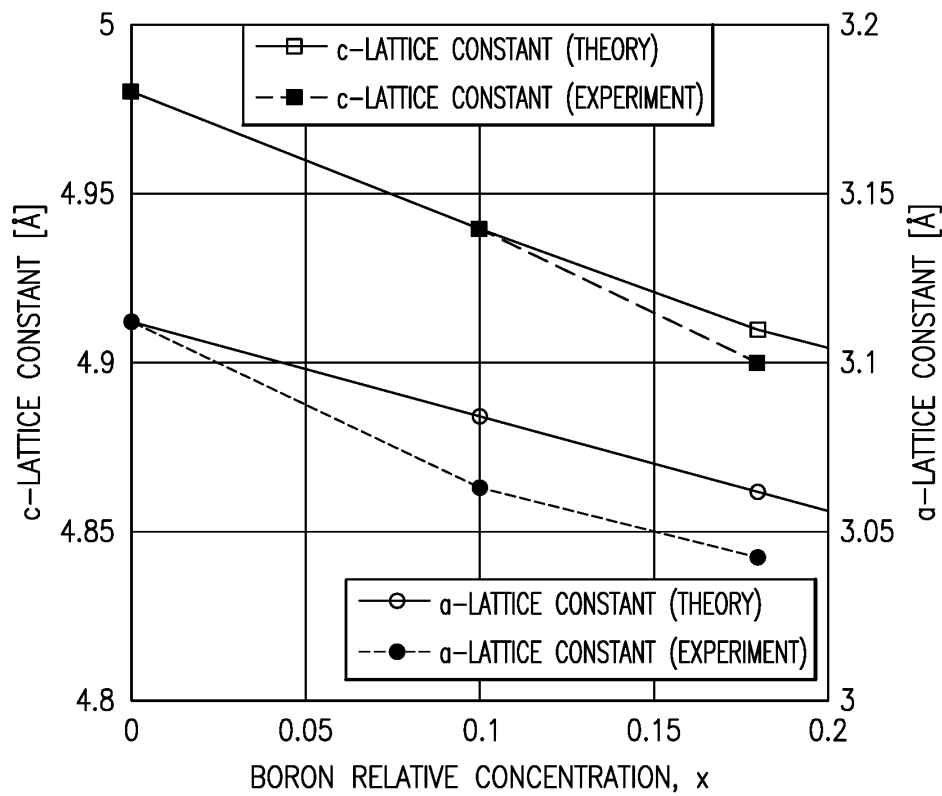


FIG.11F

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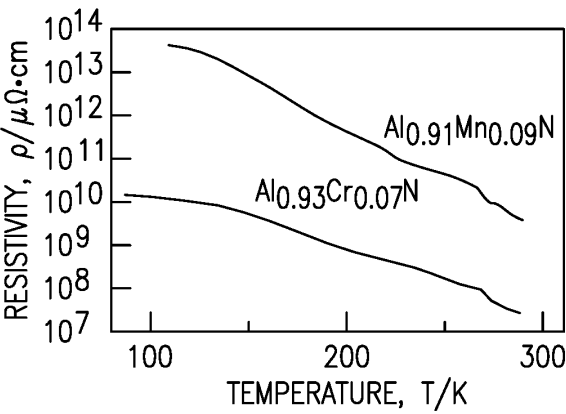


FIG.12A

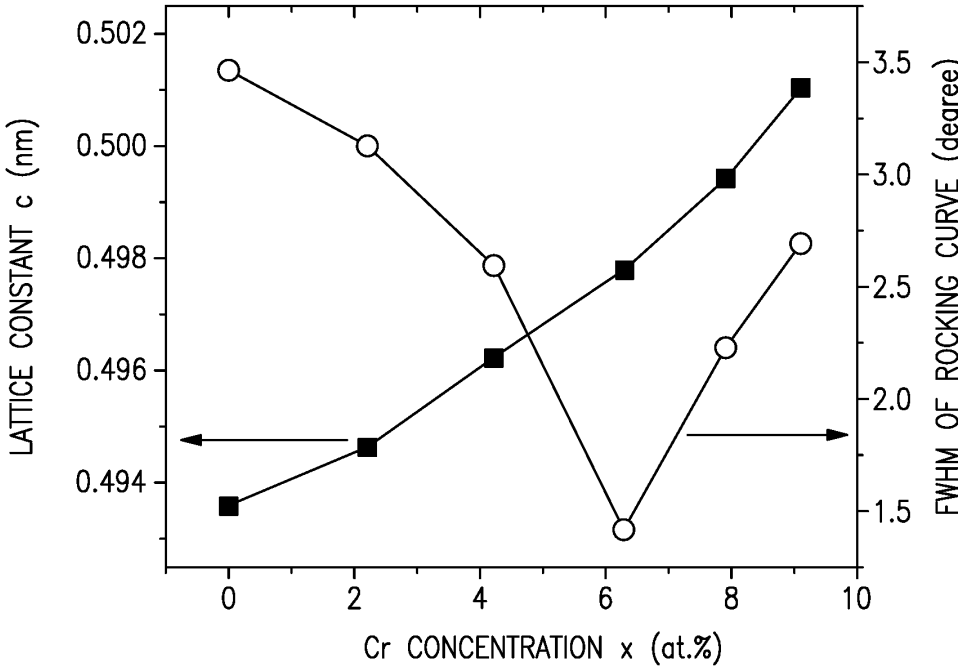
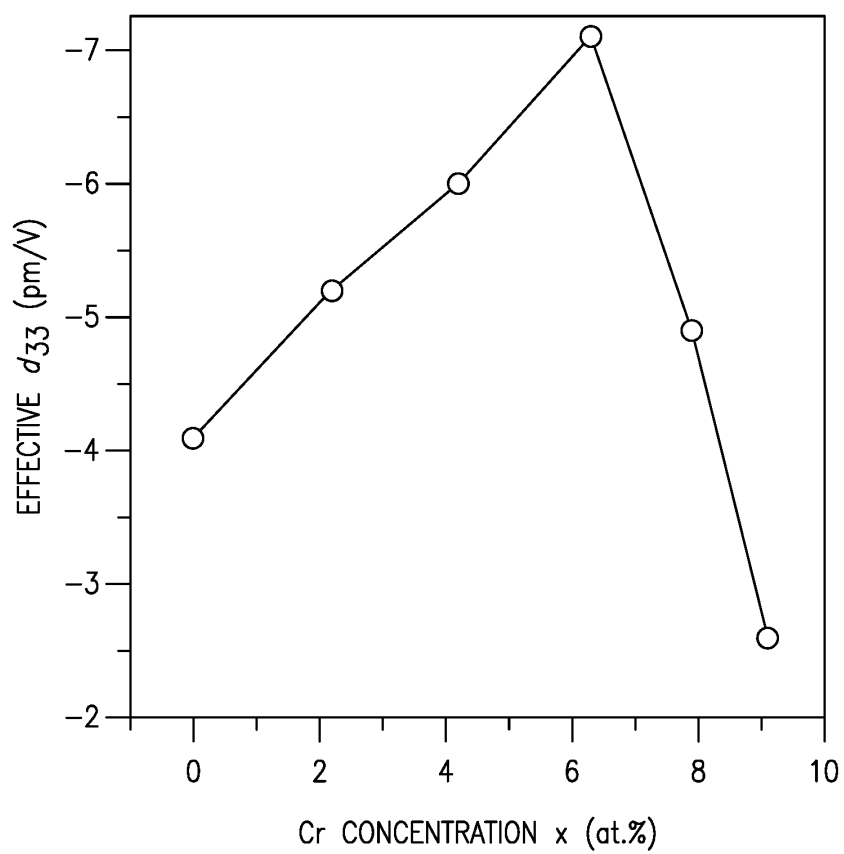
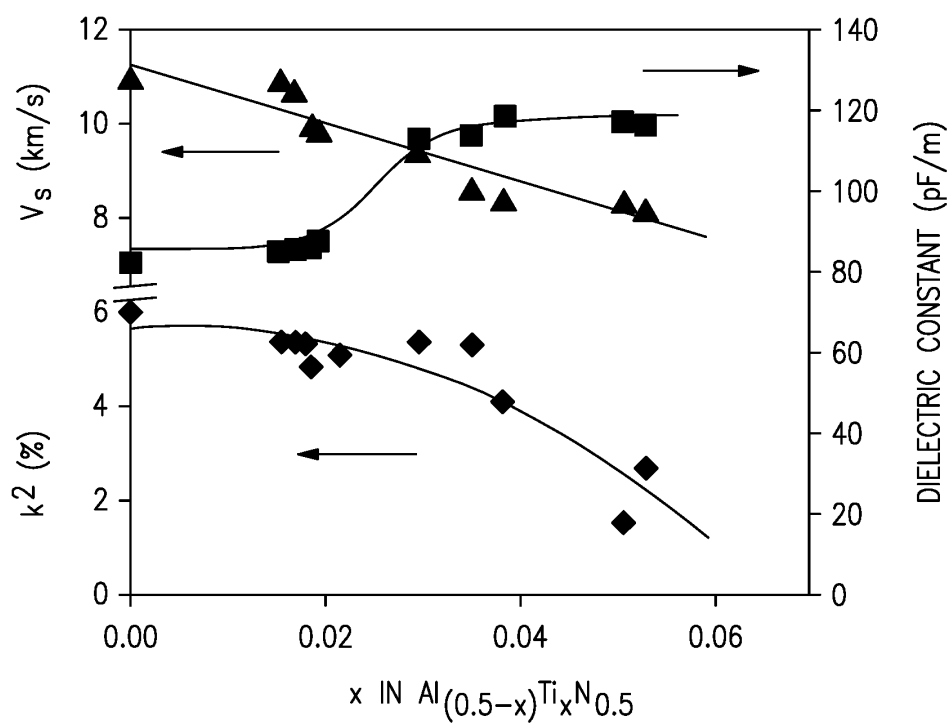


FIG.12B

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**FIG.12C**

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**FIG.13**

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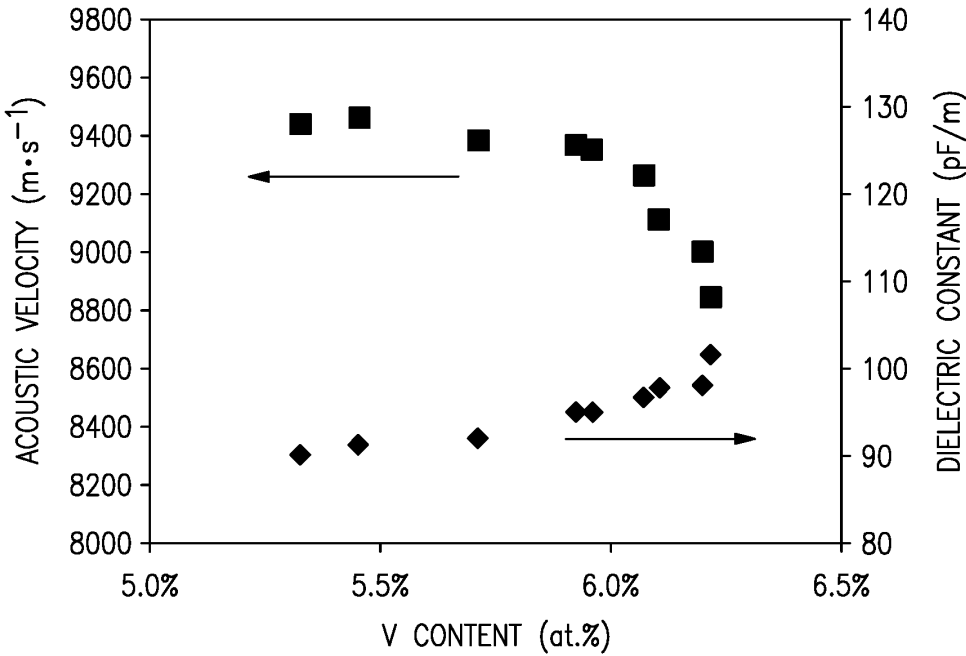


FIG.14A

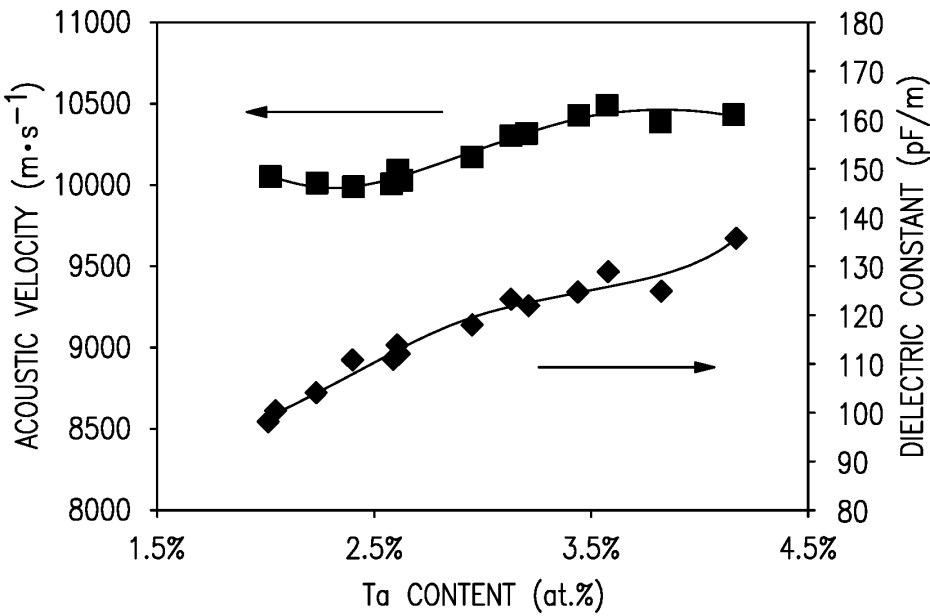


FIG.14B

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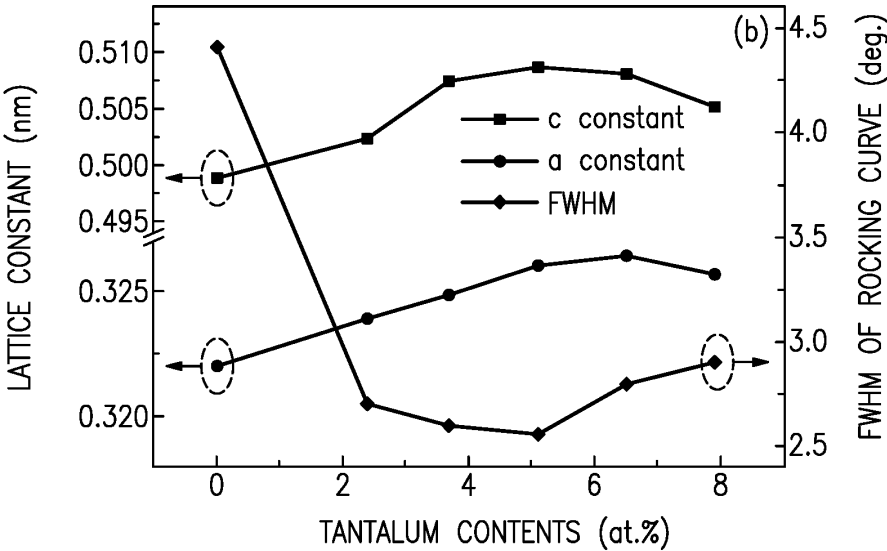


FIG.14C

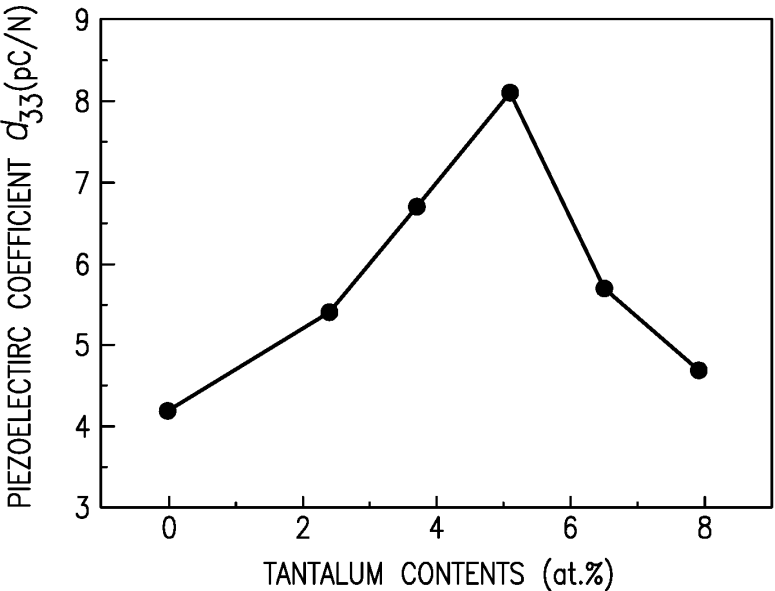


FIG.14D

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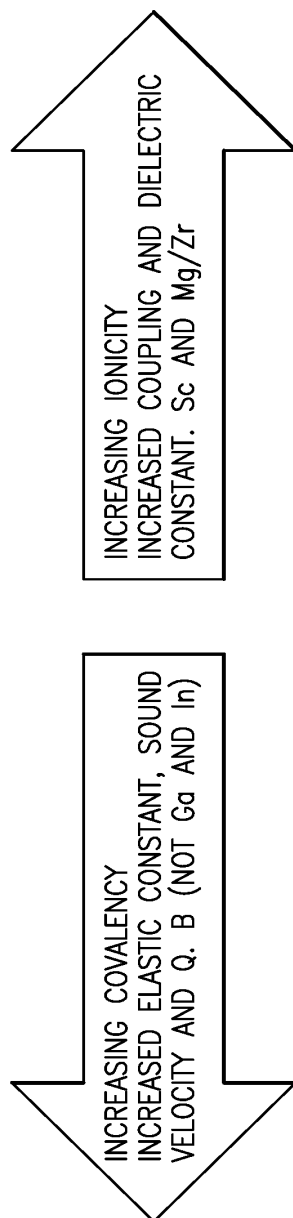


FIG.15

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Dopant	k^2	d_{33} or e_{33}	ϵ'	Elastic Constant	sound Velocity	Q	Temp Stability	Band Gap	c-axis preferred orientation	c/a
Ga (In)	reduce	reduce	mildly increase	decrease	decrease	???	mild improvement	decrease	good	mild increase
B	reduce	decrease	decrease	increase	increase	increase	???	increase	fair	increase
Sc	increase	increase	increase	decrease	decrease	decrease	negligible effect	decrease	good	decrease
Y	increase	increase	increase	decrease	decrease	decrease	???	decrease	good	decrease
Cr	decrease	increase	increase	increase	increase	???	worse than AlN	???	Inversion domains	decrease
Ti	decrease	decrease	increase	decrease	decrease	decrease	mild improvement	???	good	???
Ta	increase	increase	???	???	Flat.	???	???	???	good	Increase. Reports disagree
V	decrease	decrease	increase	decrease	decrease	???	???	???	Not optimized	???
Mg/Zr Mg/Hf	increase	increase	increase	decrease	decrease	decrease	???	???	good	decrease

FIG.16

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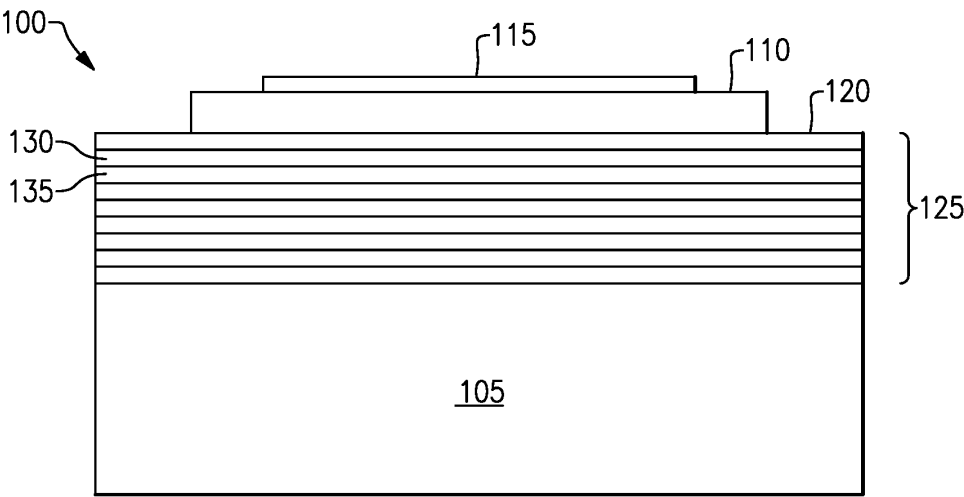


FIG.17

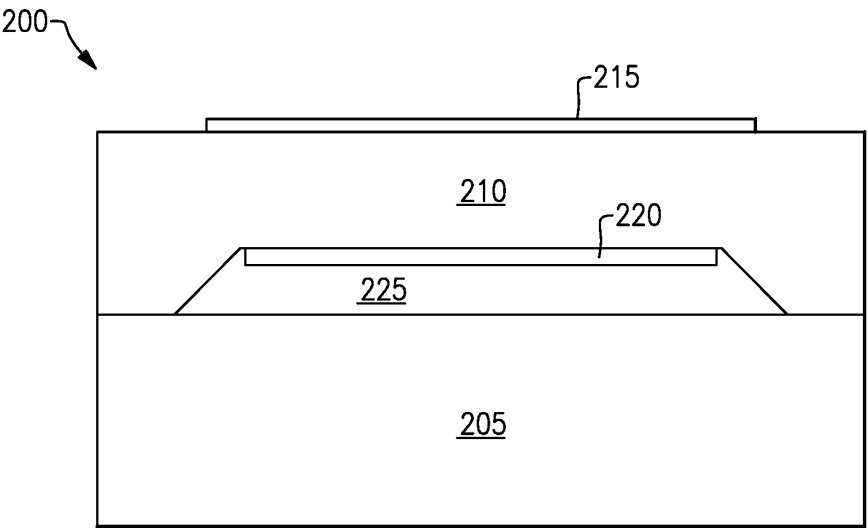


FIG.18

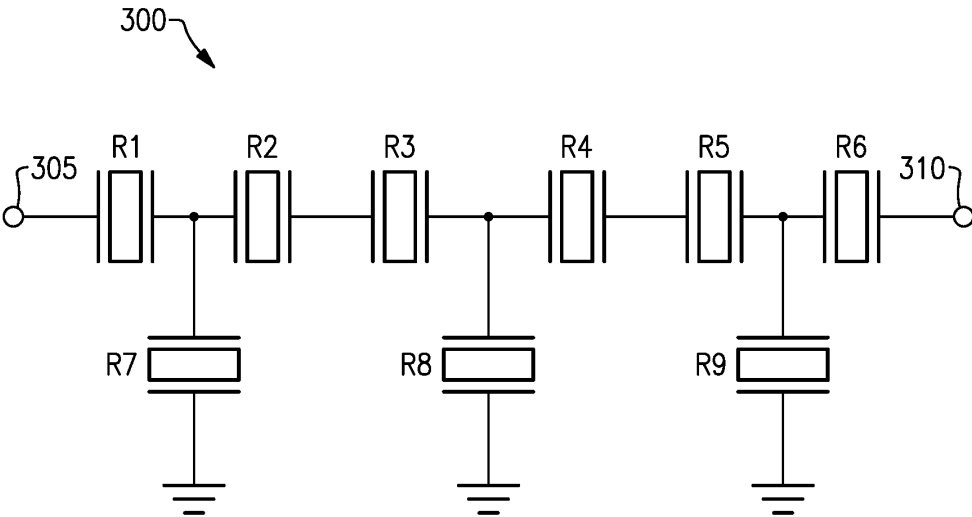
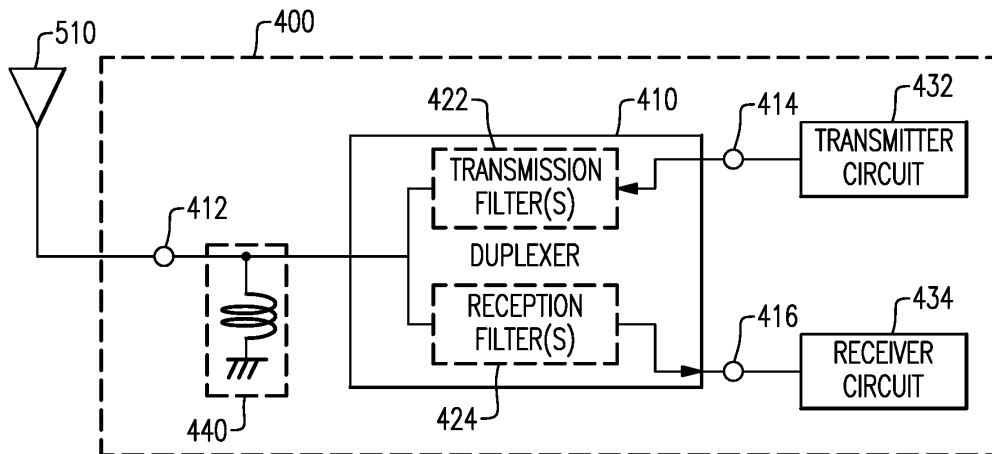
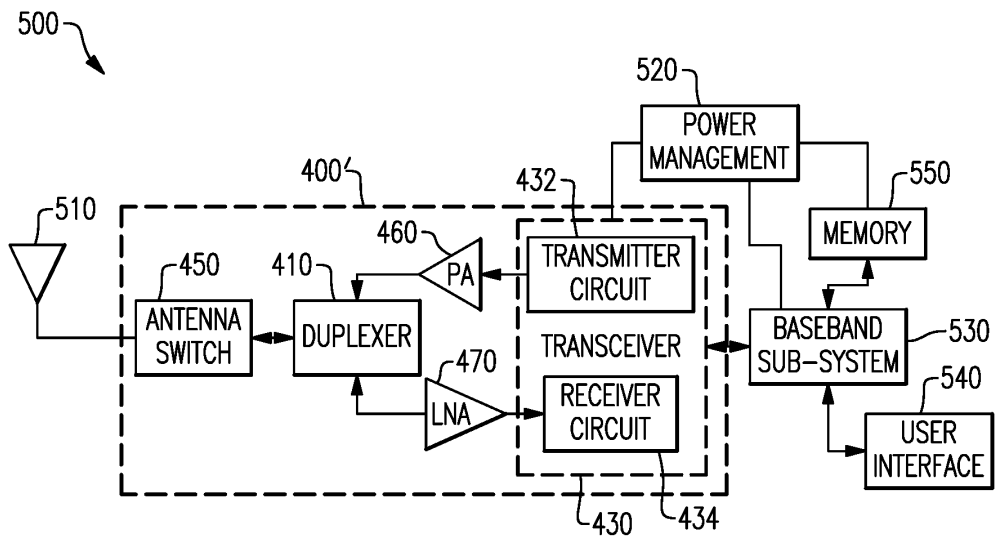


FIG.19

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**FIG. 20****FIG. 21**