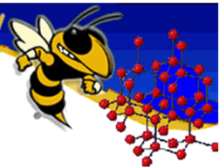


Lecture 1

Introduction to Electronic Materials

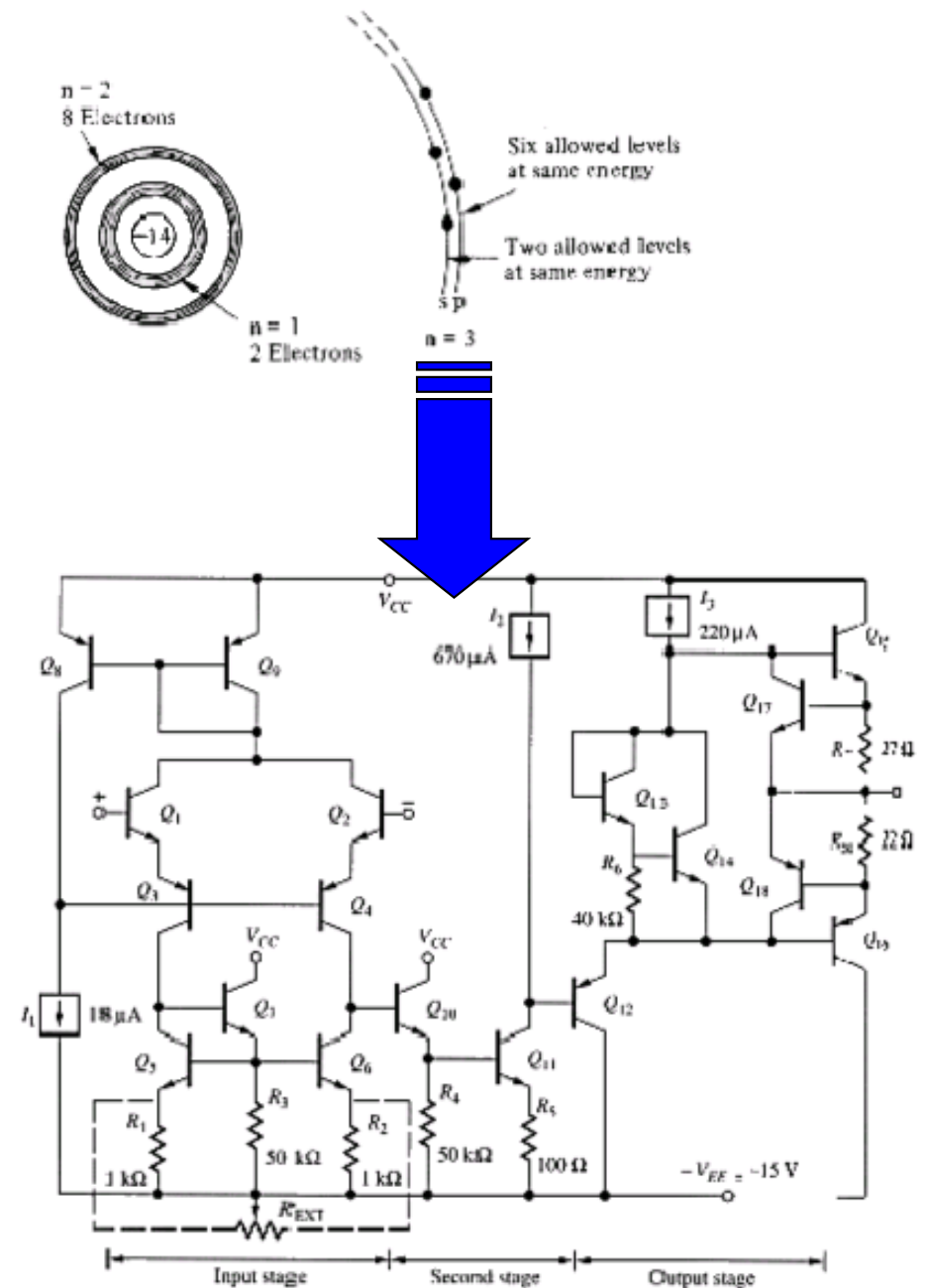
Reading:

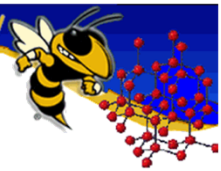
Pierret 1.1, 1.2, 1.4, 2.1-2.6



Atoms to Operational Amplifiers

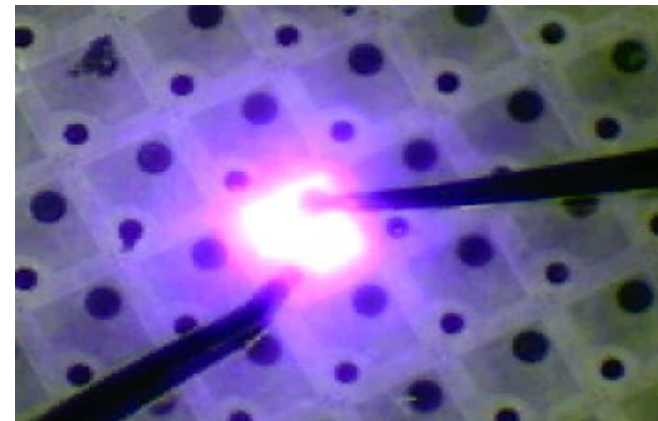
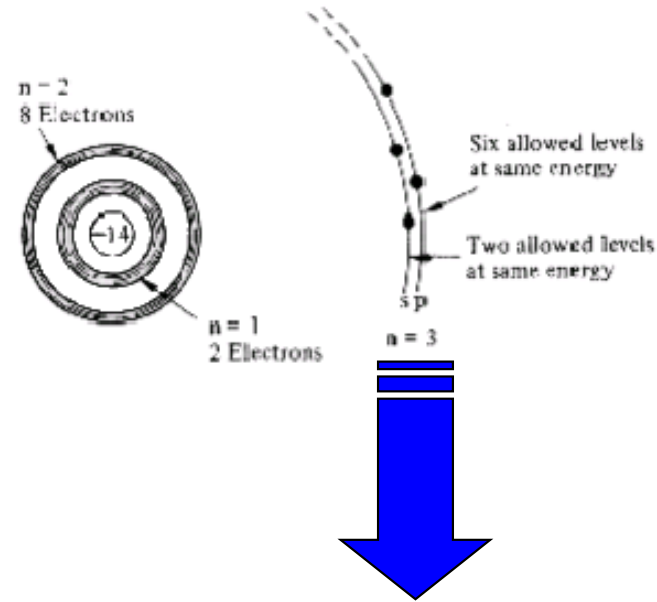
- The goal of this course is to teach the fundamentals of non-linear circuit elements including diodes, and transistors (BJT and FET), how they are used in circuits and real world applications.
- The course takes an “atoms to op-amps” approach in which you learn about the fundamentals of electron movement in semiconductor materials and develop this basic knowledge into how we can construct devices from these materials that can control the flow of electrons in useful ways.
- We then extend this knowledge to how these devices can be used to form circuits that perform useful functions on electrical signals.



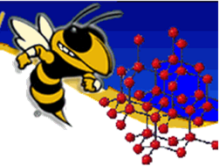


... Atoms to Everything Else in Optoelectronics

- The goal of this course is to teach the fundamentals of non-linear circuit elements including diodes, and transistors (BJT and FET), how they are used in circuits and real world applications.
- The course takes an “atoms to op-amps” approach in which you learn about the fundamentals of electron movement in semiconductor materials and develop this basic knowledge into how we can construct devices from these materials that can control the flow of electrons in useful ways.
- We then extend this knowledge to how these devices can be used to form circuits that perform useful functions on electrical signals.



Nakamura, S. *et al.*, “High-power InGaN single-quantum-well-structure blue and violet light-emitting diodes,” *Appl. Phys. Lett.* 67, 1868 (1995).



Modern amplifiers consist of extremely small devices

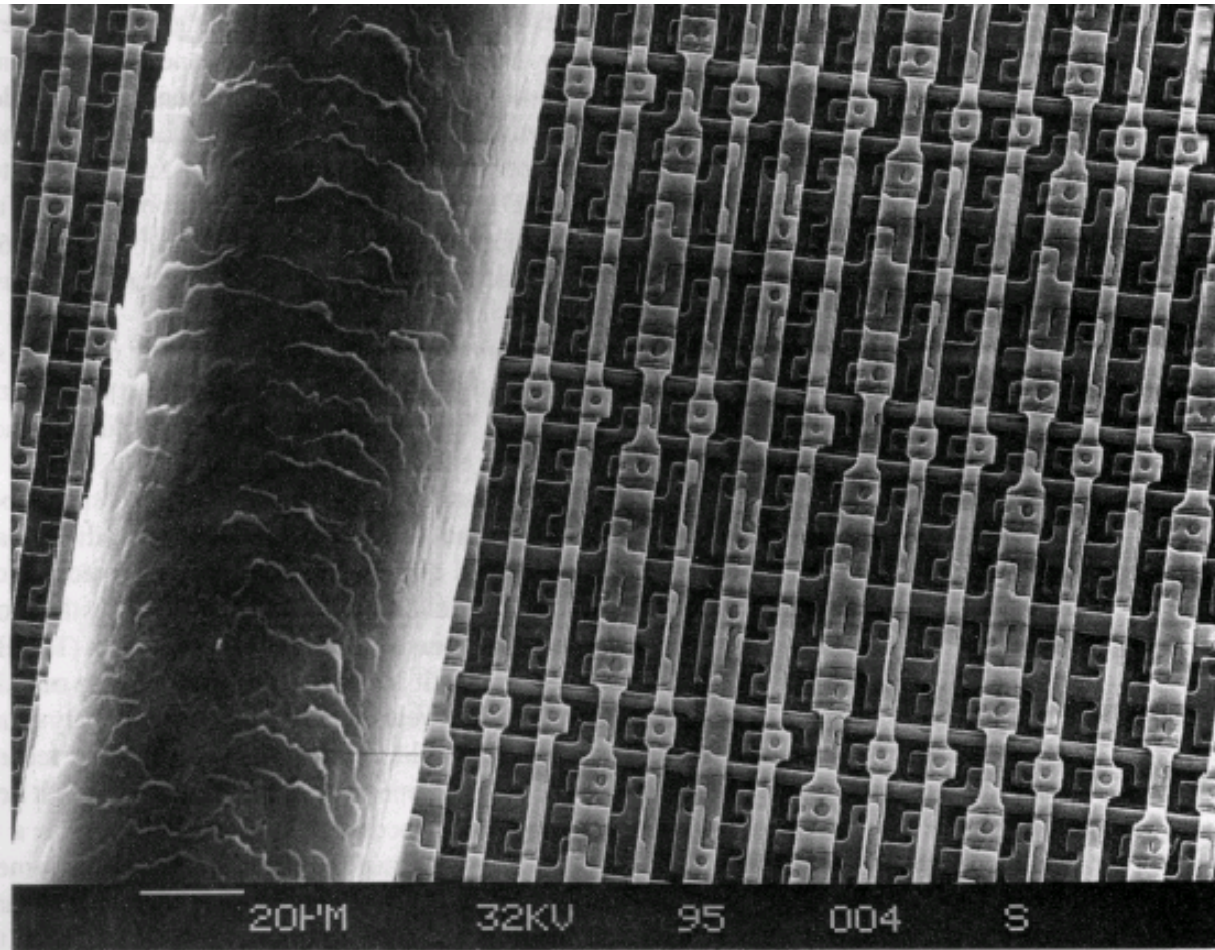
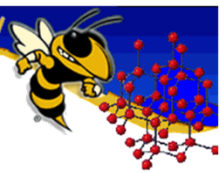


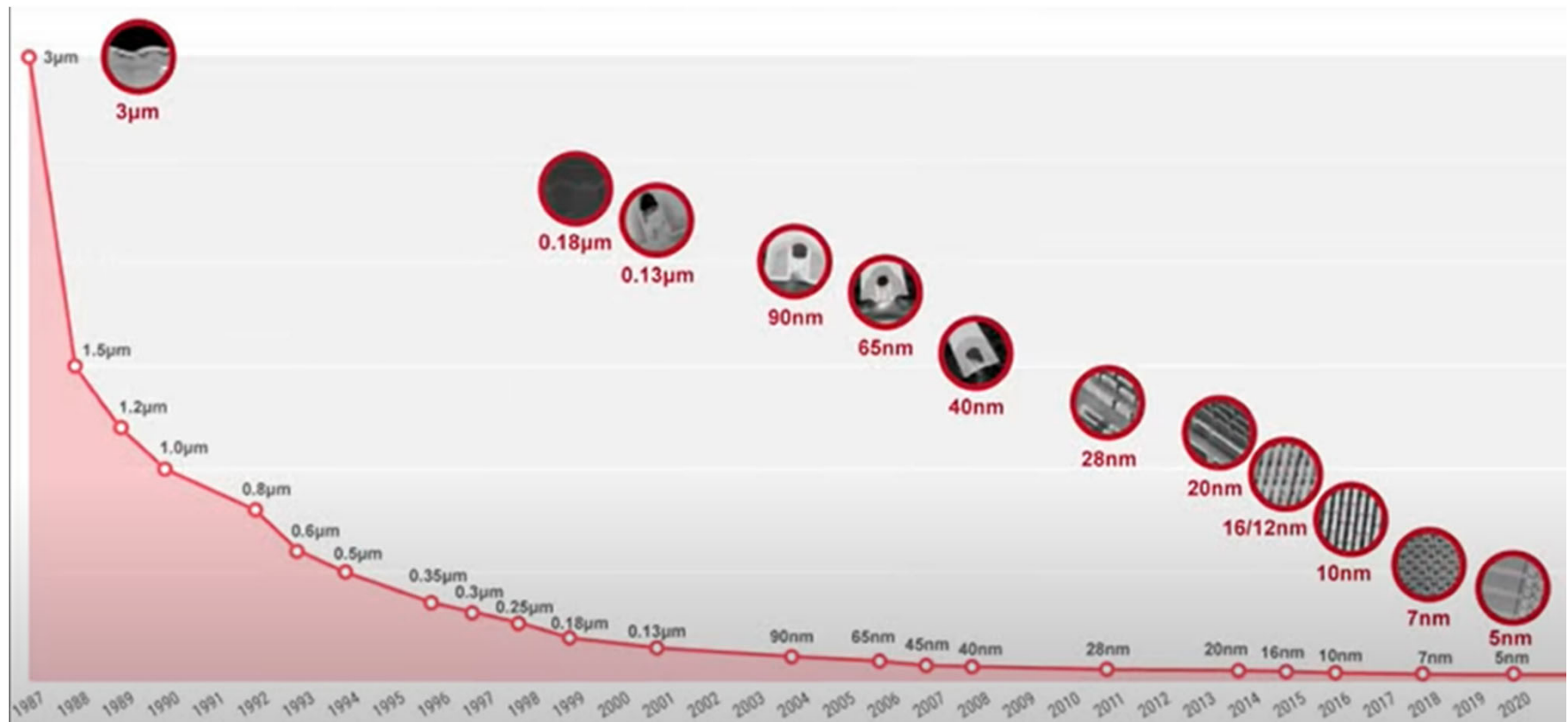
Figure 1-2 Scanning electron micrograph (SEM) of an IC circa mid 1980s. The visible lines correspond to metal wires connecting the transistors.

Transistors in the above image are only a few microns (μm or $1\text{e-}6$ meters) on a side.

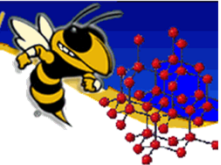
Modern devices have lateral dimensions that are only fractions of a micron ($\sim 0.01 \mu\text{m}$) and vertical dimensions that may be only a few atoms tall.



Modern amplifiers consist of extremely small devices

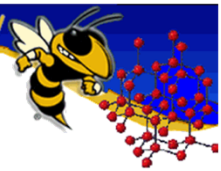


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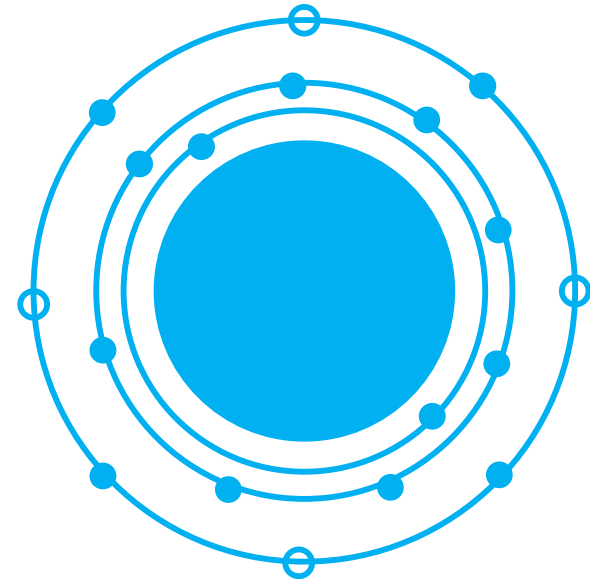
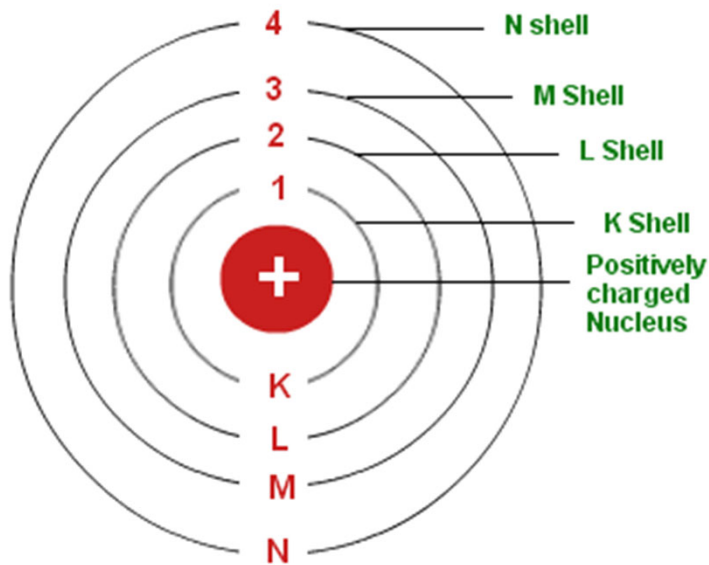


Control of Conductivity is the Key to Modern Electronic Devices

- Conductivity, σ , is the ease with which a given material conducts electricity.
- Ohms Law: $V=IR$ or $J=\sigma E$ where J is current density and E is electric field.
 - Metals: High conductivity
 - Insulators: Low Conductivity
 - Semiconductors: Conductivity can be varied by several orders of magnitude.
- It is the ability to control conductivity that make semiconductors useful as “current/voltage control elements”. “Current/Voltage control” is the key to switches (digital logic including microprocessors etc...), amplifiers, LEDs, LASERs, photodetectors, etc...

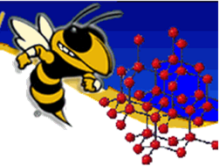


Classifications of Electronic Materials



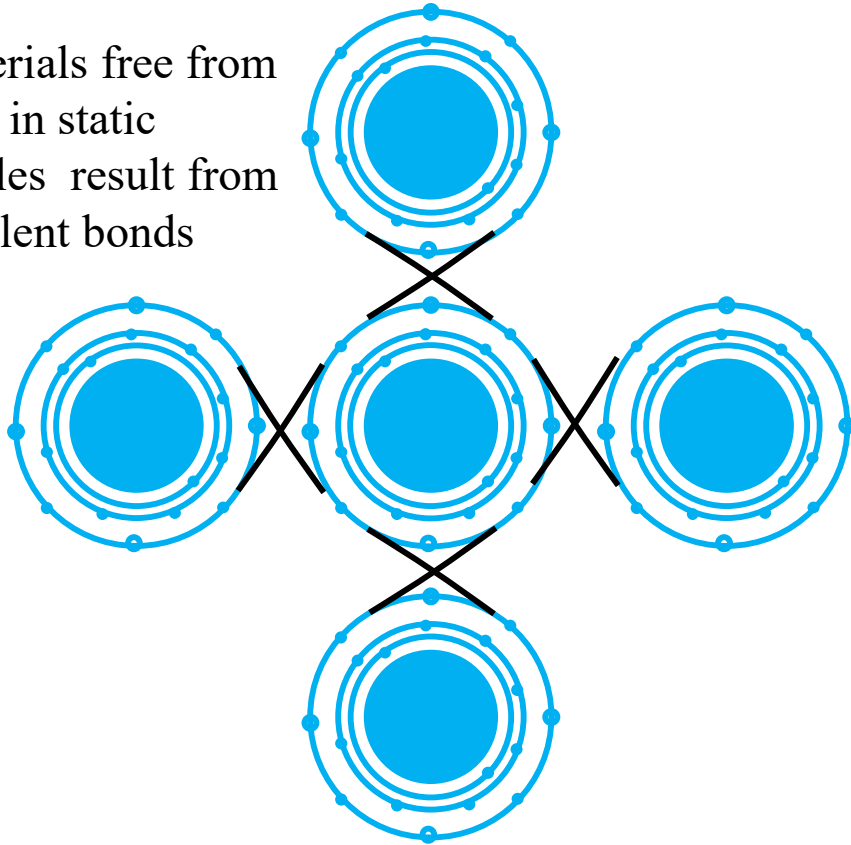
Example: Silicon $n=1$ (2 s), $n=2$ (2 s and 6 p) and $n=3$ (2 s and 2 p with 4 unoccupied p states)

- Atoms contain various “orbitals”, “levels” or “shells” of electrons labeled as $n=1, 2, 3, 4$, etc... or K, L, M, or N etc... The individual allowed electrons “states” are simply allowed positions (energy and space) within each orbital/level/shell for which an electron can occupy.
- Electrons fill up the levels (fill in the individual states in the levels) from the smallest n shell to the largest occupying “states” (available orbitals) until that orbital is completely filled then going on to the next higher orbital.
- The outer most orbital/level/shell is called the “Valence orbital”. This valence orbital is the only one that participated in the bonding of atoms together to form solids.

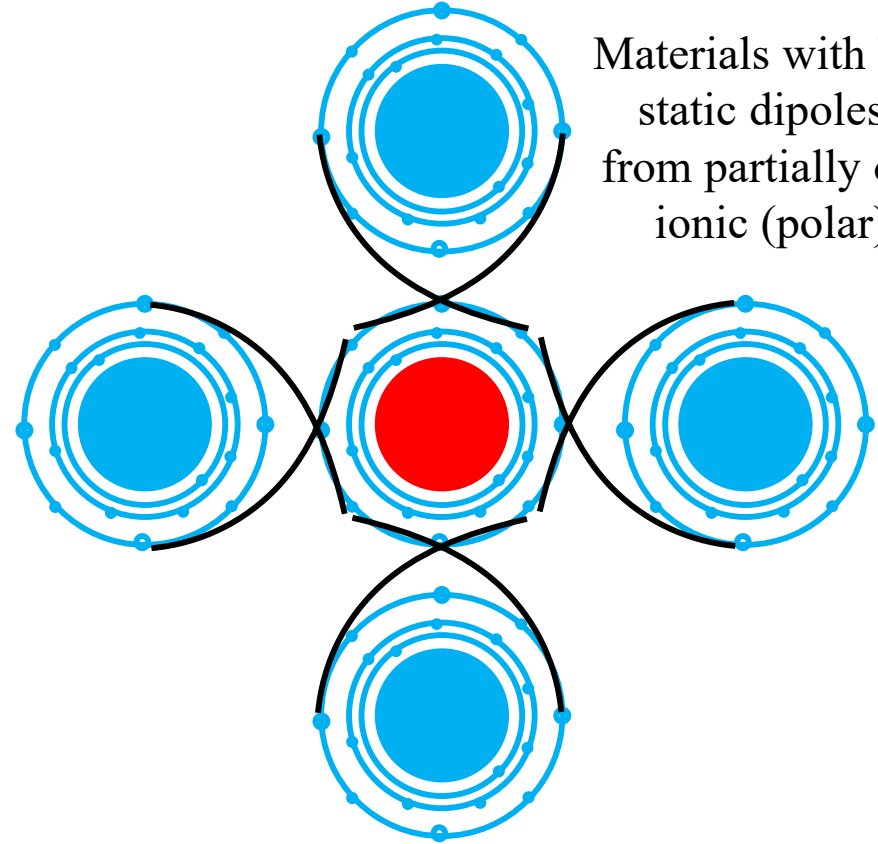


Classifications of Electronic Materials

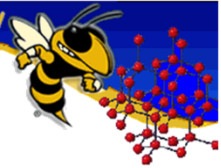
Materials free from built in static dipoles result from covalent bonds



Materials with built in static dipoles result from partially or fully ionic (polar) bonds

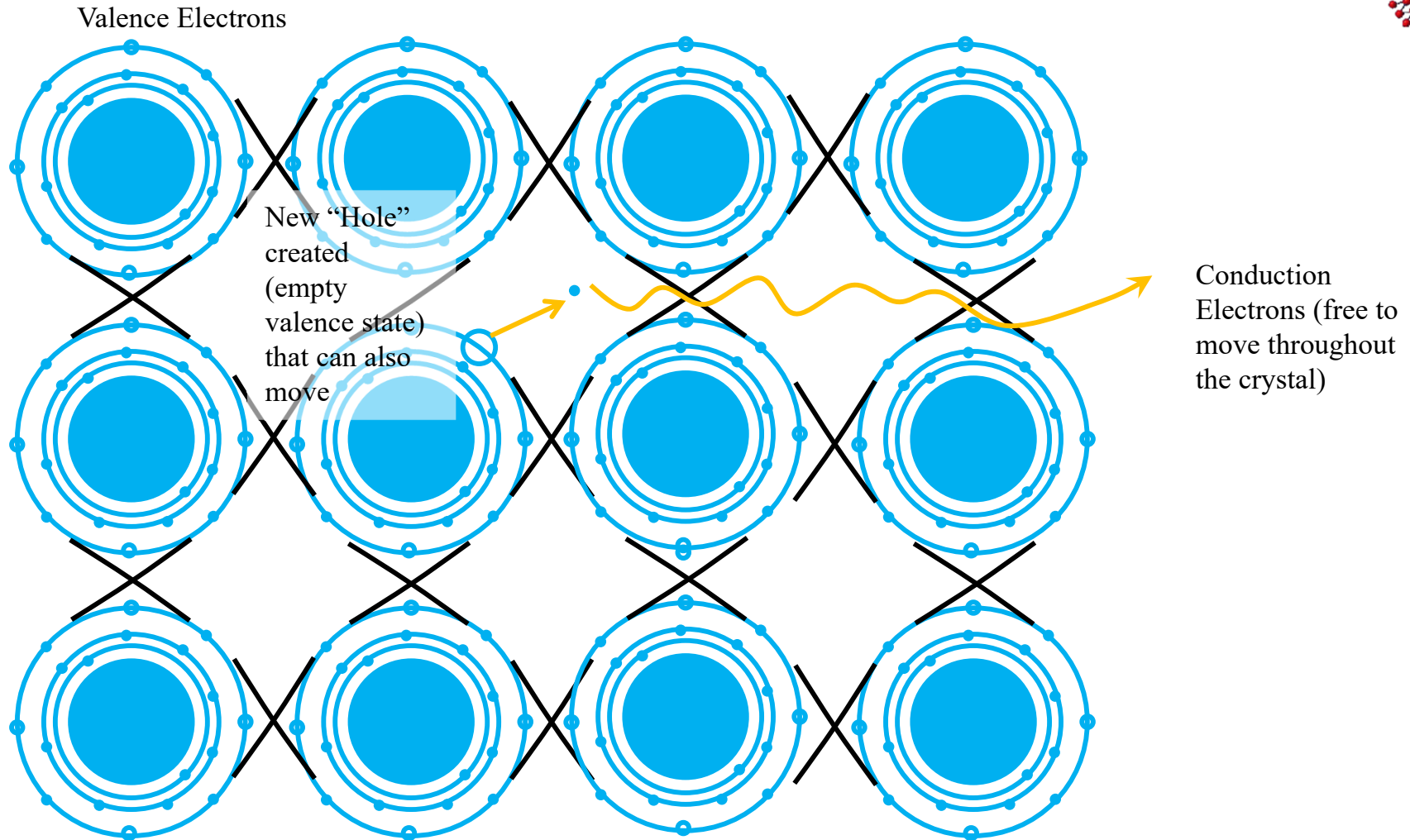


- Solids are formed by several methods, including (but not limited to) sharing electrons (covalent bonds) or by columbic attraction of ions (fully ionic) or partial ionic attraction / partial sharing of electrons (partially ionic)
- The method for which the semiconductor forms, particularly whether or not a fixed static di-pole is constructed inside the crystal, effects the way the semiconductor interacts with light.
- Later we will see that covalent bonds tend toward “indirect bandgap” (defined later) materials whereas polar bonds (ionic and partially ionic) tend toward “direct bandgap” materials.

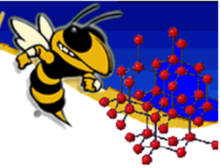


Classifications of Electronic Materials

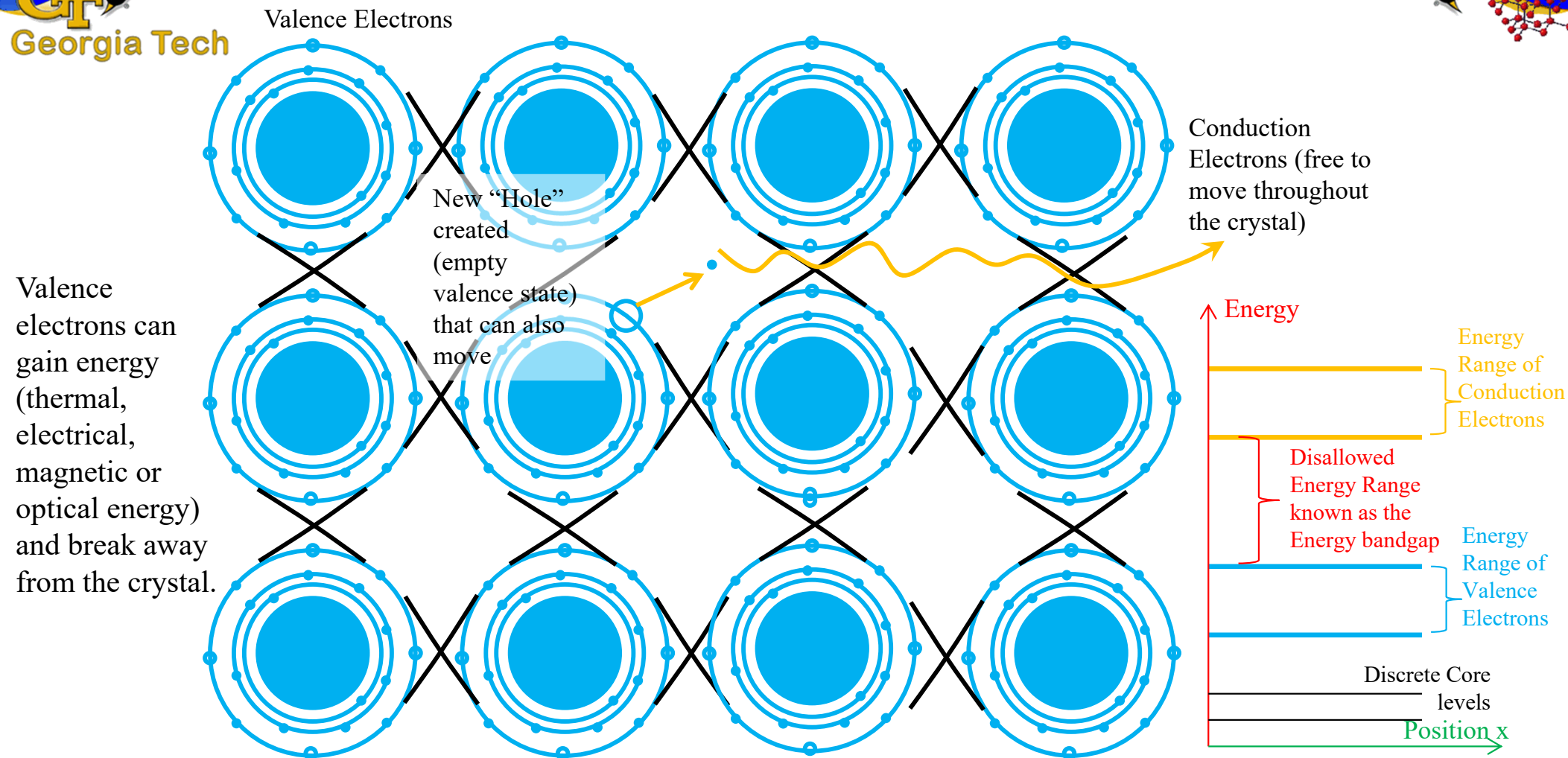
Valence electrons can gain energy (thermal, electrical, magnetic or optical energy) and break away from the crystal.



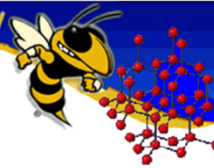
- Only the outermost core levels participate in bonding. We call these "Valence orbits" or "Valence Shells".
- For metals, the electrons can jump from the valence orbits (outermost core energy levels of the atom) to any position within the crystal (free to move throughout the crystal) with no "extra energy needed to be supplied". Thus, "free conducting electrons are prevalent at room temperature.
- For insulators, it is VERY DIFFICULT for the electrons to jump from the valence orbits and requires a huge amount of energy to "free the electron" from the atomic core. Thus, few conducting electrons exist.
- For semiconductors, the electrons can jump from the valence orbits but does require a small amount of energy to "free the electron" from the atomic core, thus making it a ***SEMI***-conductor".



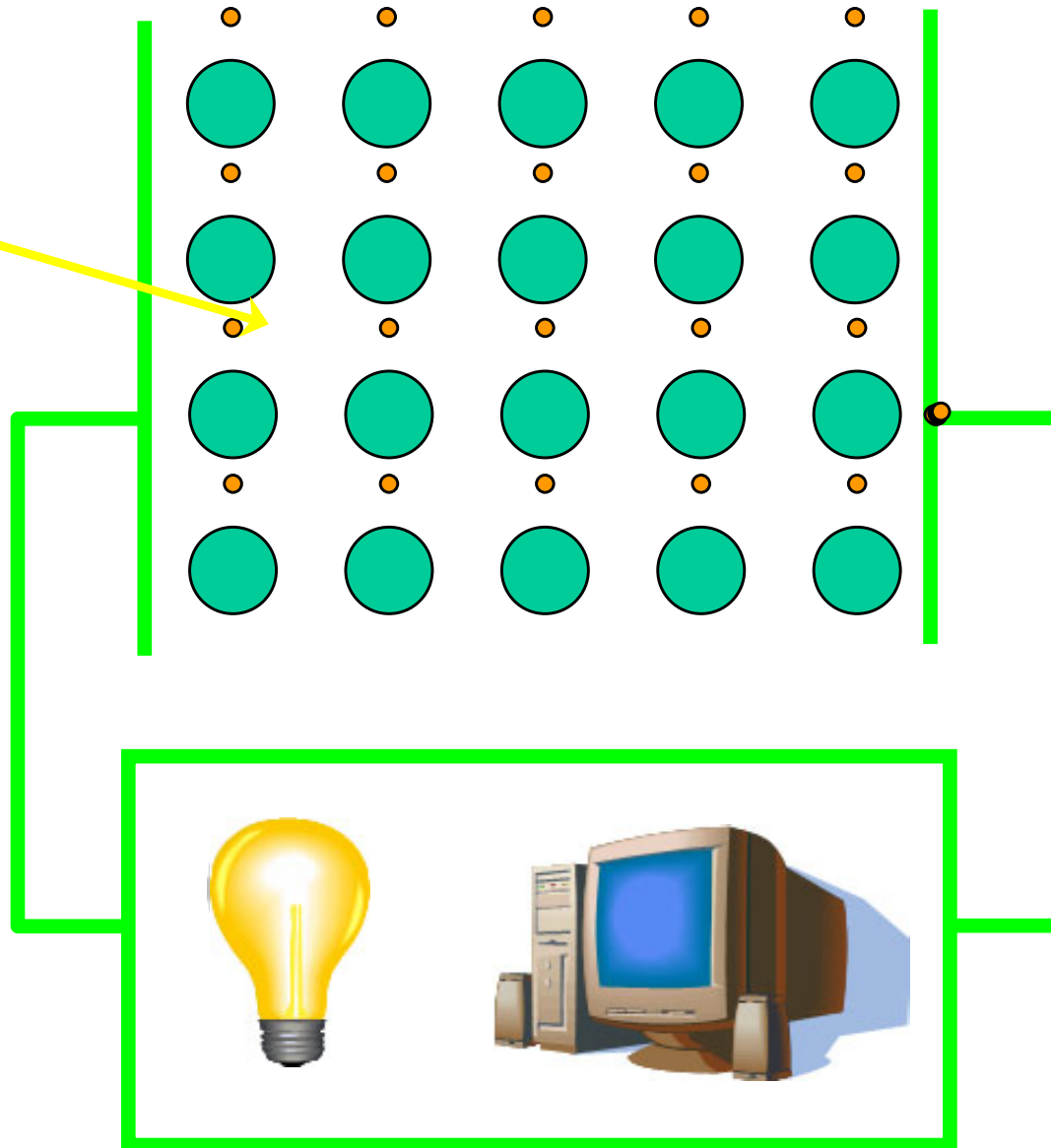
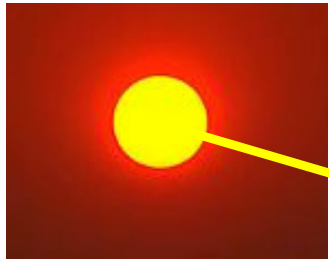
Classifications of Electronic Materials



- Since the electrons in the valence orbitals of a solid can have a range of energies and since the free conducting electrons can have a range of energies, semiconductor materials are a sub-class of materials distinguished by the existence of a range of disallowed energies between the energies of the valence electrons (outermost core electrons) and the energies of electrons free to move throughout the material.
- The energy difference (**energy gap or bandgap**) between the states in which the electron is bound to the atom and when it is free to conduct throughout the crystal is related to the bonding strength of the material, its density, the degree of ionicity of the bond, and the chemistry related to the valence of bonding.
- High bond strength materials (diamond, SiC, AlN, GaN etc...) tend to have large energy bandgaps.
- Lower bond strength materials (Si, Ge, InSb, etc...) tend to have smaller energy bandgaps.

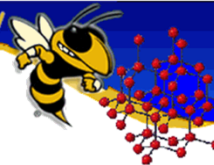


Example: Solar Cells



Why do the electrons flow when light is present but not flow when light is not present?

Answer, Energy Bandgap (very important concept).



Classifications of Electronic Materials

- More formally, the energy gap is derived from the Pauli exclusion principle, where no two electrons occupying the same space, can have the same energy. Thus, as atoms are brought closer towards one another and begin to bond together, their energy levels must split into bands of discrete levels so closely spaced in energy, they can be considered a continuum of allowed energy.

- Strongly bonded materials tend to have small interatomic distances between atoms. Thus, the strongly bonded materials can have larger energy bandgaps than do weakly bonded materials.

- One question that repeatedly comes up: Why does the bandgap form instead of just s and p orbital mixing? While complex beyond this explanation, the answer is in the way the s and p orbitals “hybridize” (mix). As the mixing becomes “severe”, they must separate more fully, leaving a range of energies where no electron can exist – the energy bandgap.

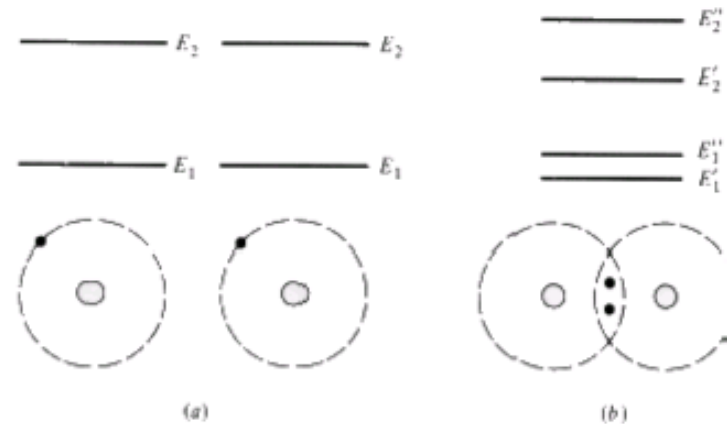
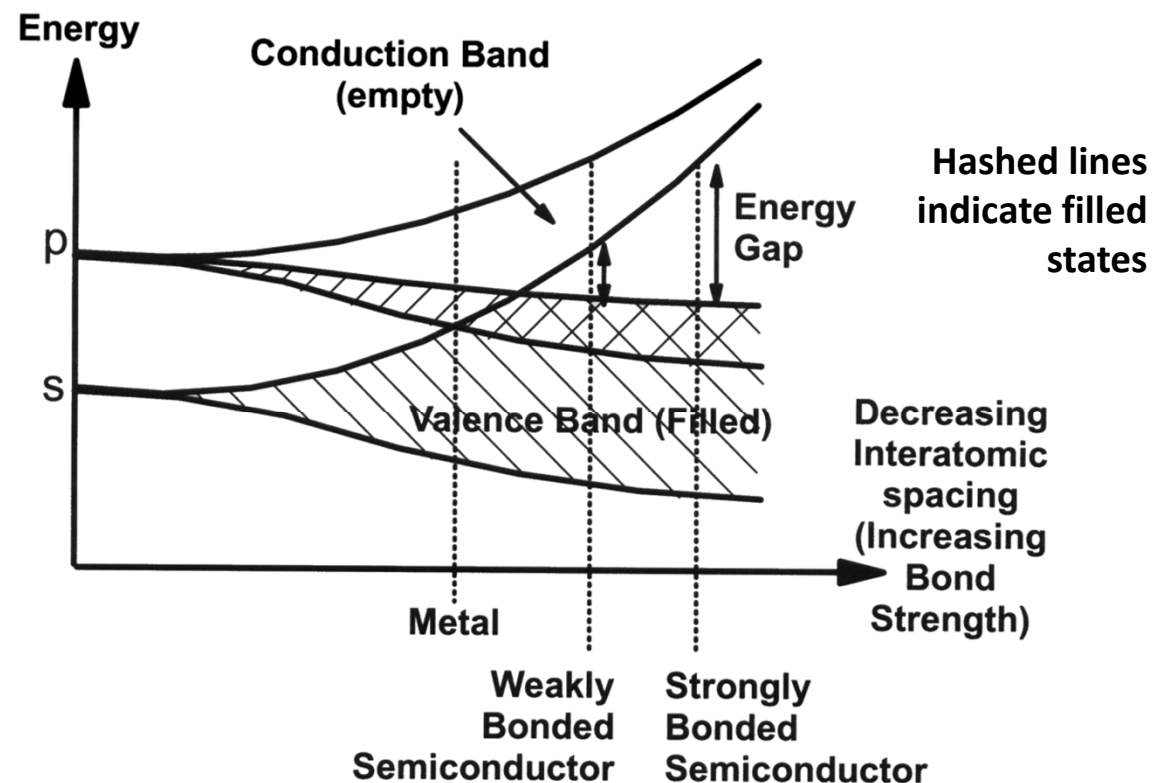
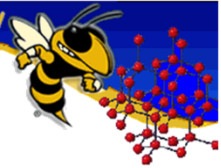


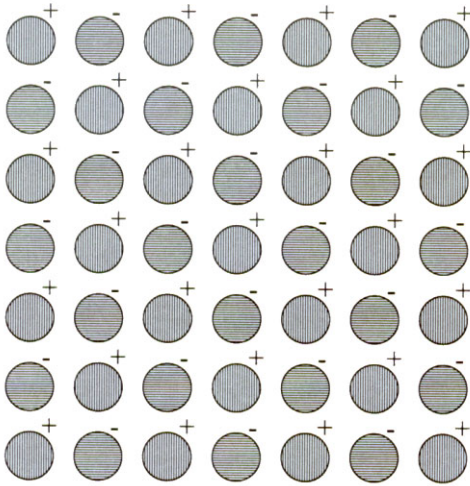
FIGURE 1-9
Two hydrogen atoms: (a) non-interacting and (b) interacting. Splitting of energy levels is illustrated for (b).



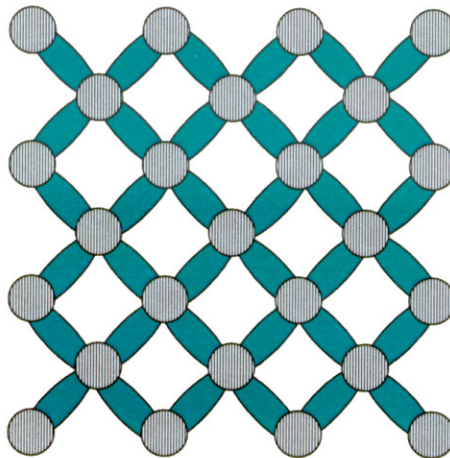


Material Classifications based on Bonding Method

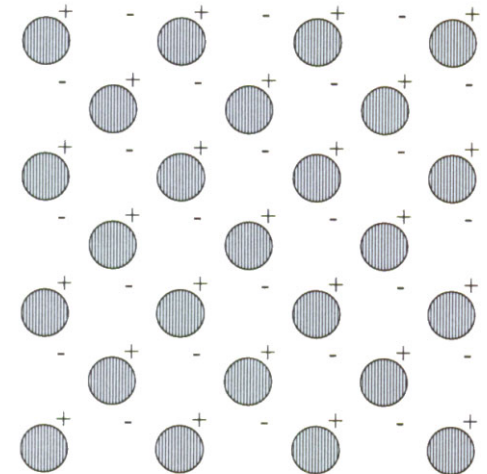
Bonds can be classified as metallic, Ionic, Covalent, and van der Waals.



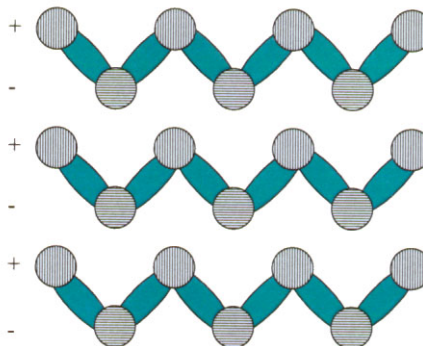
Ionic Bonding: One atom acquires and holds the electron(s) of an adjacent atom. Bonding is coulombic and strong.



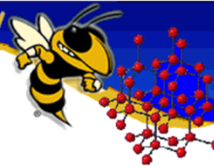
Covalent Bonding: Atoms share electrons with the surrounding atoms. Bonding is moderately weak.



Metallic Bonding: Atoms give up electrons to the surrounding regions, forming an “electron cloud”. Bonding is coulombic but weak due to screening of charge.



Van der Waals Bonding: Neutrally charged molecules form dipoles which are attracted to other dipoles. Bonding is extremely weak, but long chains can form.



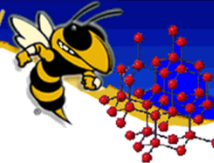
Consider the case of the group 4 elements, all** covalently bonded

Element Atomic Radius/Lattice Constant Bandgap

(How closely spaced are the atoms?)

C	0.91/3.56 Angstroms	5.47 eV
Si	1.46/5.43 Angstroms	1.12 eV
Ge	1.52/5.65 Angstroms	0.66 eV
α -Sn	1.72/6.49 Angstroms	~ 0.08 eV*
Pb	1.81/** Angstroms	Metal

0.66	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	177	178	179	180	181	182	183	184	185	186	187	188	189	190	191	192	193	194	195	196	197	198	199	200	201	202	203	204	205	206	207	208	209	210	211	212	213	214	215	216	217	218	219	220	221	222	223	224	225	226	227	228	229	230	231	232	233	234	235	236	237	238	239	240	241	242	243	244	245	246	247	248	249	250	251	252	253	254	255	256	257	258	259	260	261	262	263	264	265	266	267	268	269	270	271	272	273	274	275	276	277	278	279	280	281	282	283	284	285	286	287	288	289	290	291	292	293	294	295	296	297	298	299	300	301	302	303	304	305	306	307	308	309	310	311	312	313	314	315	316	317	318	319	320	321	322	323	324	325	326	327	328	329	330	331	332	333	334	335	336	337	338	339	340	341	342	343	344	345	346	347	348	349	350	351	352	353	354	355	356	357	358	359	360	361	362	363	364	365	366	367	368	369	370	371	372	373	374	375	376	377	378	379	380	381	382	383	384	385	386	387	388	389	390	391	392	393	394	395	396	397	398	399	400	401	402	403	404	405	406	407	408	409	410	411	412	413	414	415	416	417	418	419	420	421	422	423	424	425	426	427	428	429	430	431	432	433	434	435	436	437	438	439	440	441	442	443	444	445	446	447	448	449	450	451	452	453	454	455	456	457	458	459	460	461	462	463	464	465	466	467	468	469	470	471	472	473	474	475	476	477	478	479	480	481	482	483	484	485	486	487	488	489	490	491	492	493	494	495	496	497	498	499	500	501	502	503	504	505	506	507	508	509	510	511	512	513	514	515	516	517	518	519	520	521	522	523	524	525	526	527	528	529	530	531	532	533	534	535	536	537	538	539	540	541	542	543	544	545	546	547	548	549	550	551	552	553	554	555	556	557	558	559	560	561	562	563	564	565	566	567	568	569	570	571	572	573	574	575	576	577	578	579	580	581	582	583	584	585	586	587	588	589	590	591	592	593	594	595	596	597	598	599	600	601	602	603	604	605	606	607	608	609	610	611	612	613	614	615	616	617	618	619	620	621	622	623	624	625	626	627	628	629	630	631	632	633	634	635	636	637	638	639	640	641	642	643	644	645	646	647	648	649	650	651	652	653	654	655	656	657	658	659	660	661	662	663	664	665	666	667	668	669	670	671	672	673	674	675	676	677	678	679	680	681	682	683	684	685	686	687	688	689	690	691	692	693	694	695	696	697	698	699	700	701	702	703	704	705	706	707	708	709	710	711	712	713	714	715	716	717	718	719	720	721	722	723	724	725	726	727	728	729	730	731	732	733	734	735	736	737	738	739	740	741	742	743	744	745	746	747	748	749	750	751	752	753	754	755	756	757	758	759	760	761	762	763	764	765	766	767	768	769	770	771	772	773	774	775	776	777	778	779	780	781	782	783	784	785	786	787	788	789	790	791	792	793	794	795	796	797	798	799	800	801	802	803	804	805	806	807	808	809	810	811	812	813	814	815	816	817	818	819	820	821	822	823	824	825	826	827	828	829	830	831	832	833	834	835	836	837	838	839	840	841	842	843	844	845	846	847	848	849	850	851	852	853	854	855	856	857	858	859	860	861	862	863	864	865	866	867	868	869	870	871	872	873	874	875	876	877	878	879	880	881	882	883	884	885	886	887	888	889	890	891	892	893	894	895	896	897	898	899	900	901	902	903	904	905	906	907	908	909	910	911	912	913	914	915	916	917	918	919	920	921	922	923	924	925	926	927	928	929	930	931	932	933	934	935	936	937	938	939	940	941	942	943	944	945	946	947	948	949	950	951	952	953	954	955	956	957	958	959	960	961	962	963	964	965	966	967	968	969	970	971	972	973	974	975	976	977	978	979	980	981	982	983	984	985	986	987	988	989	990	991	992	993	994	995	996	997	998	999	1000	1001	1002	1003	1004	1005	1006	1007	1008	1009	1010	1011	1012	1013	1014	1015	1016	1017	1018	1019	1020	1021	1022	1023	1024	1025	1026	1027	1028	1029	1030	1031	1032	1033	1034	1035	1036	1037	1038	1039	1040	1041	1042	1043	1044	1045	1046	1047	1048	1049	1050	1051	1052	1053	1054	1055	1056	1057	1058	1059	1060	1061	1062	1063	1064	1065	1066	1067	1068	1069	1070	1071	1072	1073	1074	1075	1076	1077	1078	1079	1080	1081	1082	1083	1084	1085	1086	1087	1088	1089	1090	1091	1092	1093	1094	1095	1096	1097	1098	1099	1100	1101	1102	1103	1104	1105	1106	1107	1108	1109	1110	1111	1112	1113	1114	1115	1116	1117	1118	1119	1120	1121	1122	1123	1124	1125	1126	1127	1128	1129	1130	1131	1132	1133	1134	1135	1136	1137	1138	1139	1140	1141	1142	1143	1144	1145	1146	1147	1148	1149	1150	1151	1152	1153	1154	1155	1156	1157	1158	1159	1160	1161	1162	1163	1164	1165	1166	1167	1168	1169	1170	1171	1172	1173	1174	1175	1176	1177	1178	1179	1180	1181	1182	1183	1184	1185	1186	1187	1188	1189	1190	1191	1192	1193	1194	1195	1196	1197	1198	1199	1200	1201	1202	1203	1204	1205	1206	1207	1208	1209	1210	1211	1212	1213	1214	1215	1216	1217	1218	1219	1220	12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Classifications of Electronic Materials

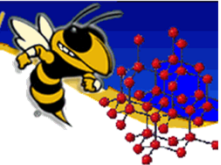
Types of Semiconductors:

- Elemental: Silicon or Germanium (Si or Ge)
- Compound: Gallium Arsenide (GaAs), Indium Phosphide (InP), Silicon Carbide (SiC), CdS and many others
- Note that the sum of the valence adds to 8, a complete outer shell. I.E. 4+4, 3+5.

PERIODIC TABLE OF THE ELEMENTS

Table of Selected Radioactive Isotopes

GROUP IA																GROUP IIA																GROUP IIIA																GROUP IVA																GROUP VA																GROUP VIA																GROUP VIIA																GROUP VIIIA																GROUP IIIB																GROUP IIB																GROUP IIIB																GROUP IVB																GROUP VB																GROUP VIB																GROUP VIIB																GROUP VIII																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																															
1 1.0079 20.908 14.005 0.000899 Hydrogen																3 6.941 1615 53.7 5.53 192Lu Beryllium																4 9.01216 2745 1560 1.85 190Pb Beryllium																11 22.98977 39 37.1 0.979 Na23 Sodium																12 24.305 1363 38.96 1.74 Mg24 Magnesium																19 39.0983 1022 39.96 0.86 K39 Potassium																20 40.08 1757 112 0.006 Ca40 Calcium																21 44.9559 304 112 3.0 Sc45 Scandium																22 47.04 3662 1043 4.50 Ti48 Titanium																23 50.9415 54.32 2945 5.8 V51 Vanadium																24 51.9961 63.32 2945 7.19 Cr52 Chromium																25 54.9380 76.423 2935 7.43 Mn55 Manganese																26 55.845 75.94 2935 7.86 Fe56 Iron																27 58.9332 75.94 2935 8.90 Co59 Cobalt																28 58.9332 75.94 2935 8.90 Ni58 Nickel																29 63.546 63.546 2935 8.96 Cu63 Copper																30 65.38 65.38 2935 8.96 Zn66 Zinc																31 69.723 69.723 2935 8.96 Ga71 Gallium																32 72.57 72.57 2935 8.96 Ge73 Germanium																33 74.9216 74.9216 2935 8.96 As75 Arsenic																34 78.96 78.96 2935 8.96 Se78 Selenium																35 79.904 79.904 2935 8.96 Br80 Bromine																36 83.80 83.80 2935 8.96 Kr84 Krypton																37 85.4678 85.4678 2935 8.96 Rb85 Rubidium																38 87.62 87.62 2935 8.96 Sr88 Strontium																39 88.9059 88.9059 2935 8.96 Y89 Yttrium																40 91.224 91.224 2935 8.96 Zr90 Zirconium																41 92.9064 92.9064 2935 8.96 Nb93 Niobium																42 95.94 95.94 2935 8.96 Mo98 Molybdenum																43 98.04 98.04 2935 8.96 Tc99 Technetium																44 101.07 101.07 2935 8.96 Ru101 Ruthenium																45 102.9055 102.9055 2935 8.96 Rh103 Rhodium																46 106.427 106.427 2935 8.96 Pd106 Palladium																47 107.868 107.868 2935 8.96 Ag108 Silver																48 112.4 112.4 2935 8.96 Cd112 Cadmium																49 114.82 114.82 2935 8.96 In115 Indium																50 118.66 118.66 2935 8.96 Sn119 Tin																51 121.757 121.757 2935 8.96 Sb122 Antimony																52 127.868 127.868 2935 8.96 Te128 Tellurium																53 128.9045 128.9045 2935 8.96 I127 Iodine																54 131.30 131.30 2935 8.96 Xe131 Xenon																55 132.9054 132.9054 2935 8.96 Cs133 Cesium																56 137.33 137.33 2935 8.96 Ba137 Barium																57 138.9055 138.9055 2935 8.96 La139 Lanthanum																58 178.48 178.48 2935 8.96 Hf178 Hafnium																59 180.9479 180.9479 2935 8.96 Ta181 Tantalum																60 183.85 183.85 2935 8.96 W184 Tungsten																61 186.207 186.207 2935 8.96 Re187 Rhenium																62 190.23 190.23 2935 8.96 Os192 Osmium																63 192.22 192.22 2935 8.96 Ir193 Iridium																64 195.08 195.08 2935 8.96 Pt196 Platinum																65 196.967 196.967 2935 8.96 Au197 Gold																66 200.51 200.51 2935 8.96 Hg201 Mercury																67 204.37 204.37 2935 8.96 Tl205 Thallium																68 207.2 207.2 2935 8.96 Pb208 Lead																69 208.9804 208.9804 2935 8.96 Bi209 Bismuth																70 209 209 2935 8.96 Po209 Polonium																71 210 210 2935 8.96 At210 Astatine																72 210 210 2935 8.96 Rn222 Radon																73 223 223 2935 8.96 Fr223 Francium																74 226.0254 226.0254 2935 8.96 Ra226 Radium																75 227.0277 227.0277 2935 8.96 Ac227 Actinium																76 227.0337 227.0337 2935 8.96 Th232 Thorium																77 232.0377 232.0377 2935 8.96 Pa231 Protactinium																78 231.0368 231.0368 2935 8.96 U235 Uranium																79 238.0289 238.0289 2935 8.96 Np237 Neptunium																80 237.0479 237.0479 2935 8.96 Pu239 Plutonium																81 244.0642 244.0642 2935 8.96 Am243 Americium																82 247.0703 247.0703 2935 8.96 Cm247 Curium																83 250.1078 250.1078 2935 8.96 Bk247 Berkelium																84 252.0839 252.0839 2935 8.96 Cf251 Californium																85 252.0839 252.0839 2935 8.96 Es252 Einsteinium																86 252.0839 252.0839 2935 8.96 Fm257 Fermium																87 257.1037 257.1037 2935 8.96 Md258 Mendelevium																88 258.1052 258.1052 2935 8.96 No259 Nobelium																89 261.1018 261.1018 2935 8.96 Lr262 Lawrencium																90 262.1037 262.1037 2935 8.96 101Uuq Ununquadium																91 262.1037 262.1037 2935 8.96 102Uub Unbibium																92 263.1037 263.1037 2935 8.96 103Uuh Untrium																93 263.1037 263.1037 2935 8.96 104Uuq Ununquadium																94 263.1037 263.1037 2935 8.96 105Uub Unbibium																95 263.1037 263.1037 2935 8.96 106Uuh Untrium																96 263.1037 263.1037 2935 8.96 107Uuq Ununquadium																97 263.1037 263.1037 2935 8.96 108Uub Unbibium																98 263.1037 263.1037 2935 8.96 109Uuh Untrium																99 263.1037 263.1037 2935 8.96 110Uuq Ununquadium																100 263.1037 263.1037 2935 8.96 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Classifications of Electronic Materials

Compound Semiconductors: Offer high performance (optical characteristics, higher frequency, higher power) than elemental semiconductors and greater device design flexibility due to mixing of materials.

Binary: GaAs, SiC, etc...

Ternary: $\text{Al}_x\text{Ga}_{1-x}\text{As}$, $\text{In}_x\text{Ga}_{1-x}\text{N}$ where $0 \leq x \leq 1$

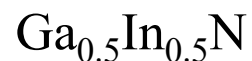
Quaternary: $\text{In}_x\text{Ga}_{1-x}\text{As}_y\text{P}_{1-y}$ where $0 \leq x \leq 1$ and $0 \leq y \leq 1$

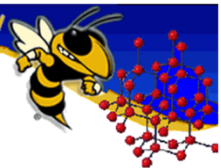
Half the total number of atoms must come from group III (Column III) and the other half the atoms must come from group V (Column V) (or more precisely, IV/IV, III/V, or II/VI combinations) leading to the above “reduced semiconductor notation that emphasizes the equal numbers of anion (higher valence electron group) and cations (lower valence electron group) in the compound.

Example: Assume a compound semiconductor has 25% “atomic” concentrations of Ga, 25% “atomic” In and 50% “atomic” of N. The chemical formula would be:

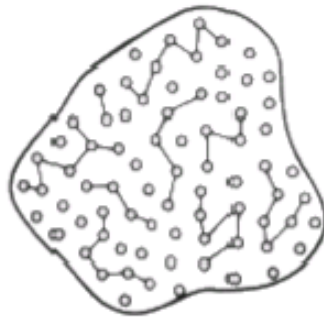


But the correct reduced semiconductor formula would be:



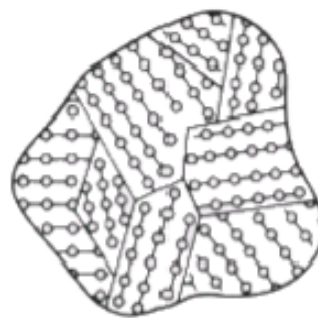


Classifications of Electronic Materials



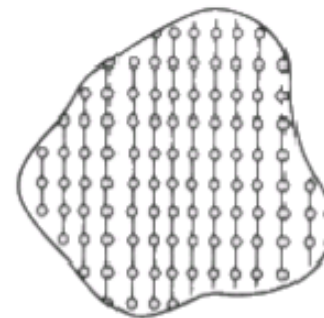
(a) Amorphous

No recognizable
long-range order



(b) Polycrystalline

Completely ordered
in segments



(c) Crystalline

Entire solid is made up of
atoms in an orderly array

General classification of solids based on the degree of atomic order: (a) amorphous, (b) polycrystalline, and (c) crystalline.

Material Classifications based on Crystal Structure

Amorphous Materials

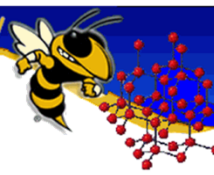
No discernible long range atomic order (no detectable crystal structure). Examples are silicon dioxide (SiO_2), amorphous-Si, silicon nitride (Si_3N_4), and others. Though usually thought of as less perfect than crystalline materials, this class of materials is extremely useful.

Polycrystalline Materials

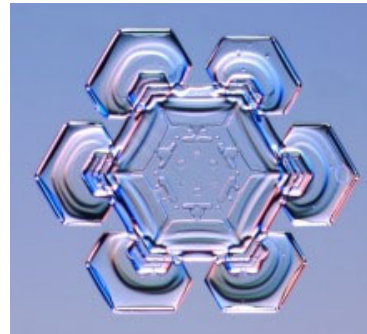
Material consisting of several “domains” of crystalline material. Each domain can be oriented differently than other domains. However, within a single domain, the material is crystalline. The size of the domains may range from cubic nanometers to several cubic centimeters. Many semiconductors are polycrystalline as are most metals.

Crystalline Materials

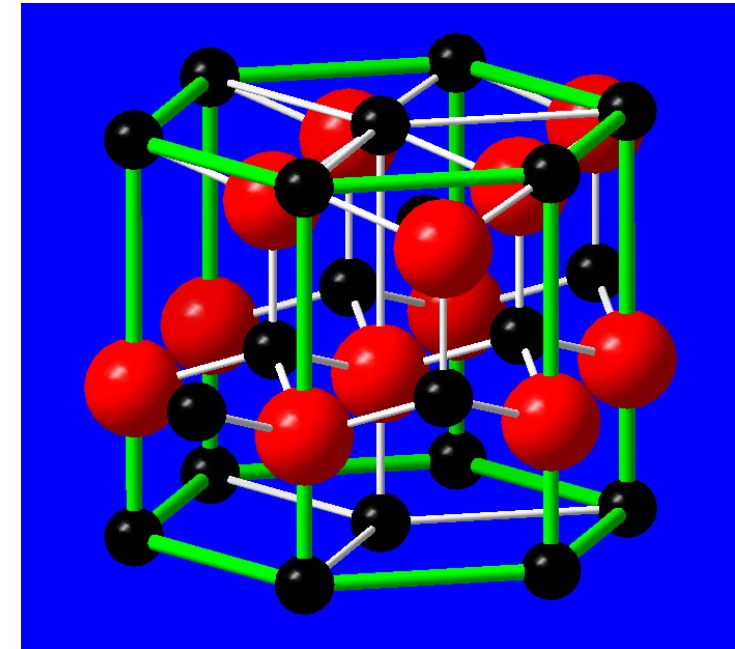
Crystalline materials are characterized by an atomic symmetry that repeats spatially. The shape of the unit cell depends on the bonding of the material. The most common unit cell structures are diamond, zincblende (a derivative of the diamond structure), hexagonal, and rock salt (simple cubic).



Crystalline Order

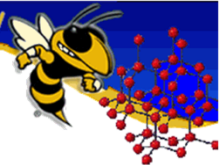


Water Molecules, H_2O , forming “Snowflakes”



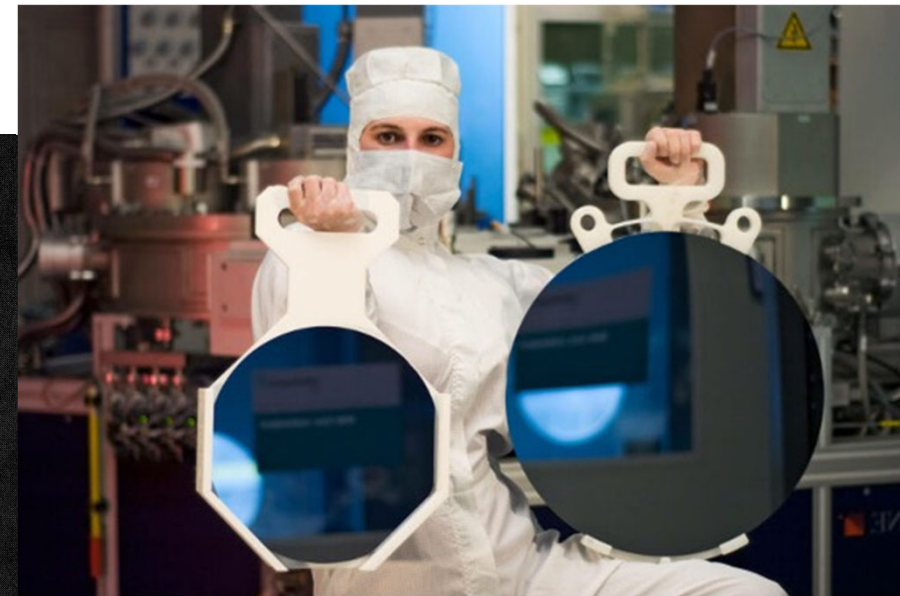
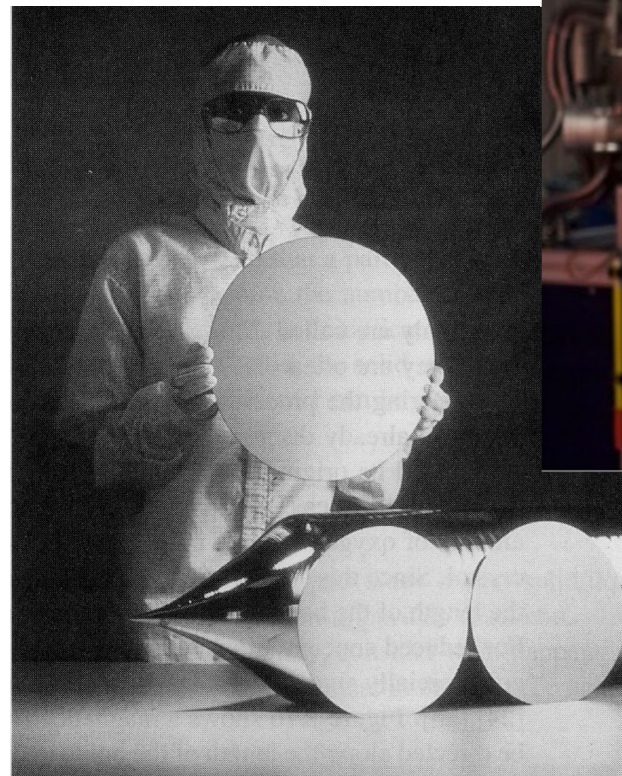
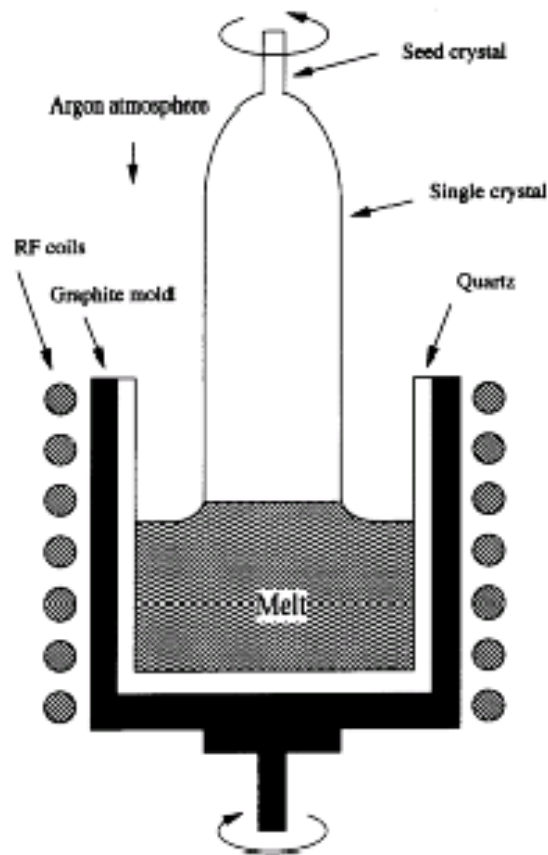
Atoms forming a
“Semiconductor”

Need two volunteers... (demo on how a crystal forms naturally due to repulsive electronic bonds)



Crystal Growth: How do we get “Single Crystalline Material”?

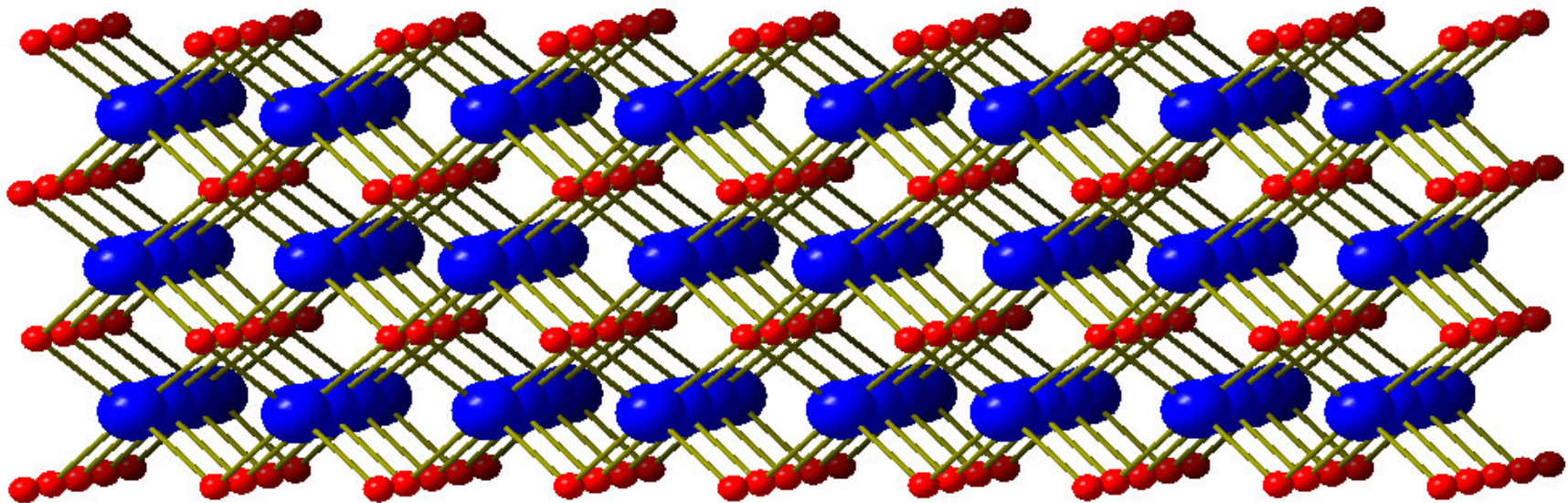
The vast majority of crystalline silicon produced is grown by the Czochralski growth method. In this method, a single crystal seed wafer is brought into contact with a liquid Silicon charge held in a crucible (typically SiO_2 but may have a lining of silicon-nitride or other material). The seed is pulled out of the melt, allowing Si to solidify. The solidified material bonds to the seed crystal in the same atomic pattern as the seed crystal.



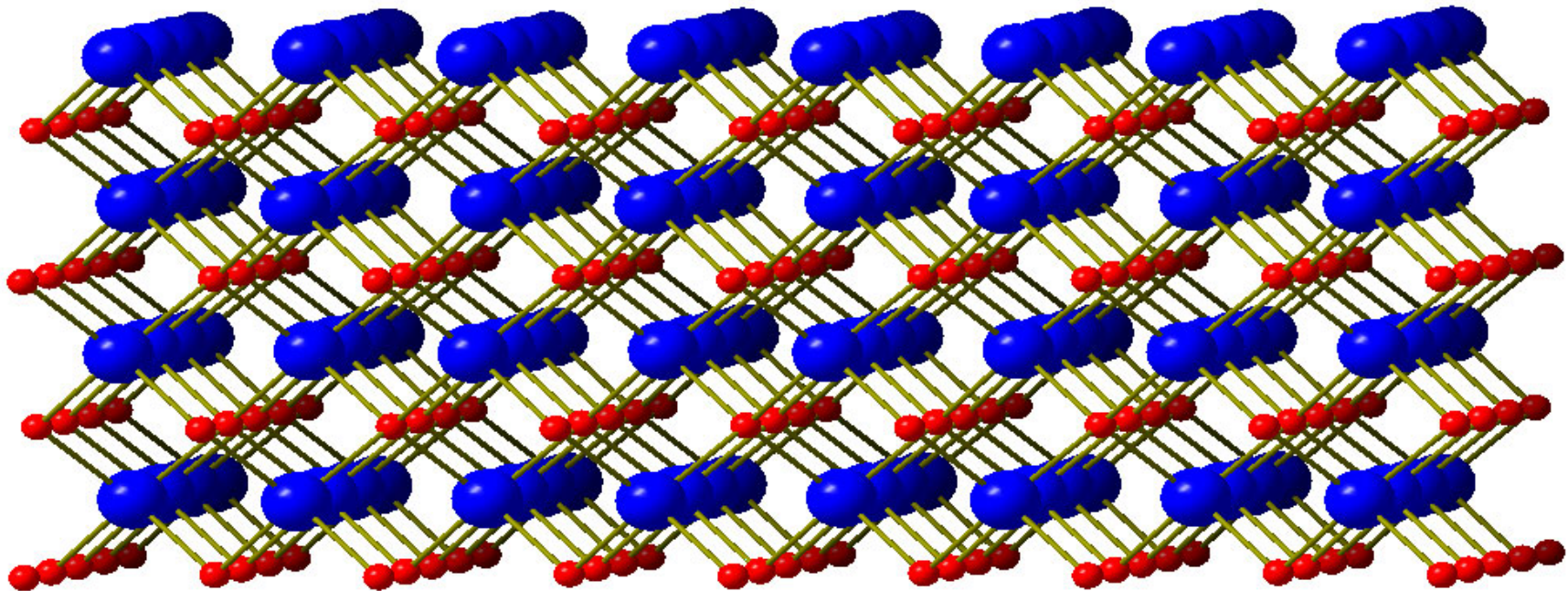
Schematic representation of the Czochralski (a) and float-zone (b) single-crystal growth techniques.

How do we create Bandgap Engineered Structures? Epitaxy

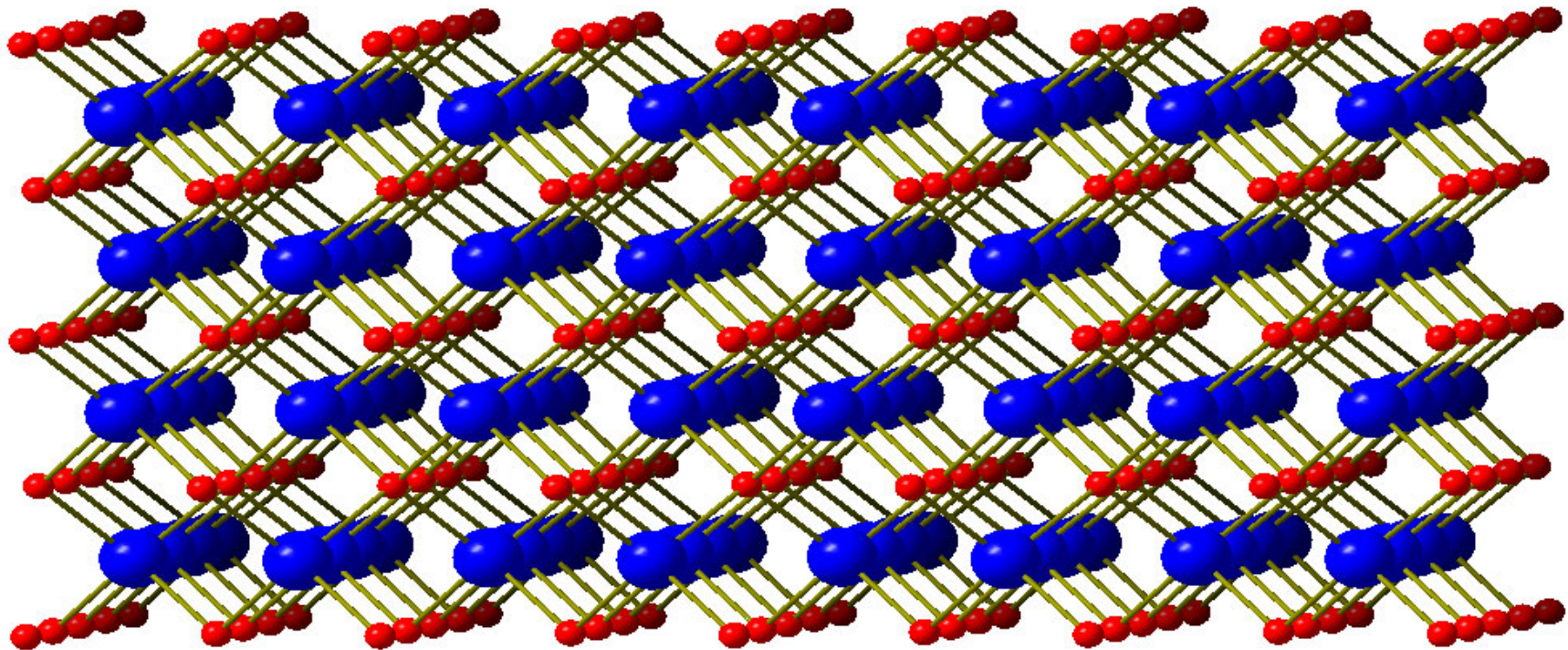
- Repeating a crystalline structure by the atom by atom addition.
- Chemistry controls the epitaxy to insure that, for example, Ga bonds only to N and not Ga-Ga or N-N bonds*.



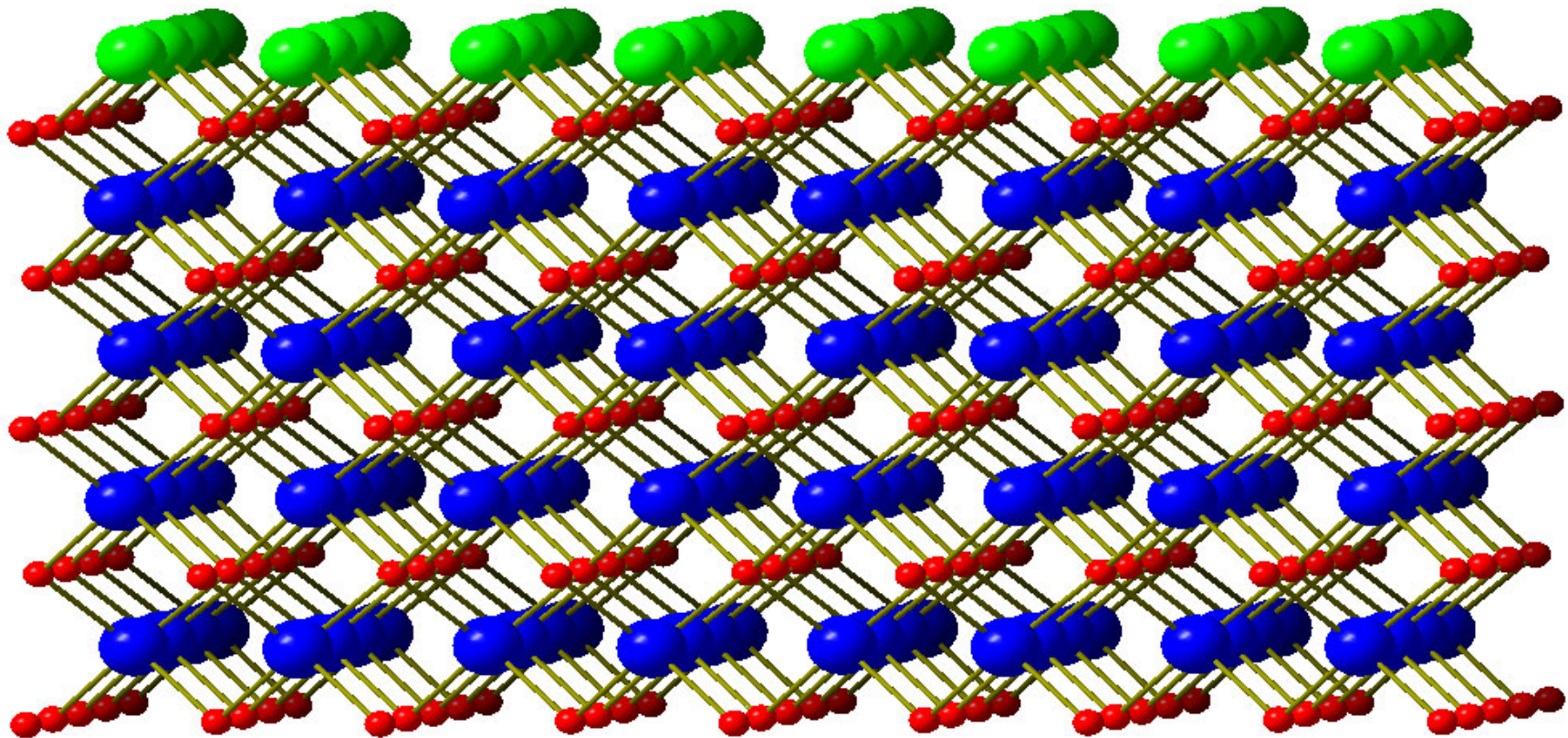
How do we create Bandgap Engineered Structures? Epitaxy



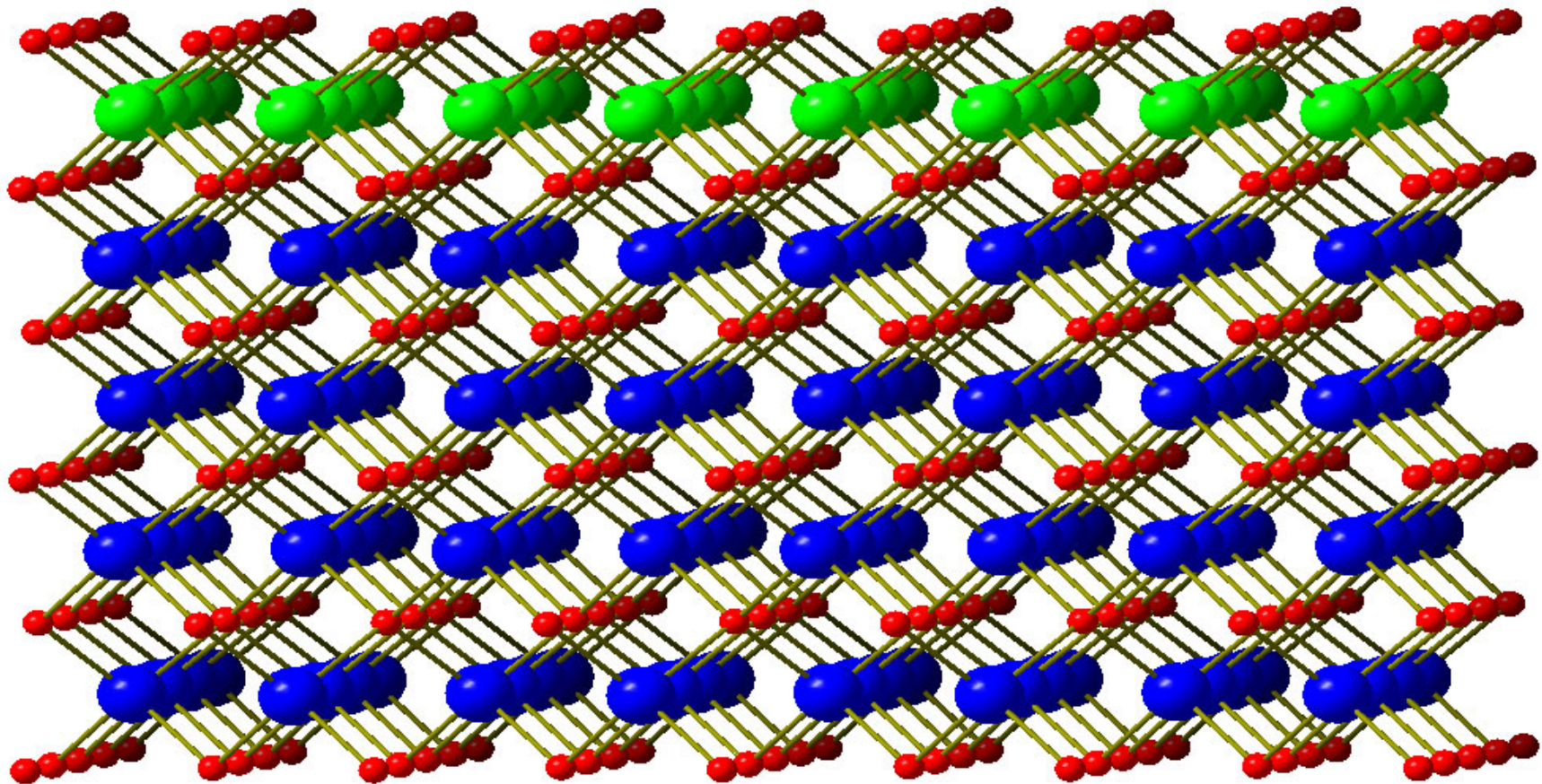
How do we create Bandgap Engineered Structures? Epitaxy



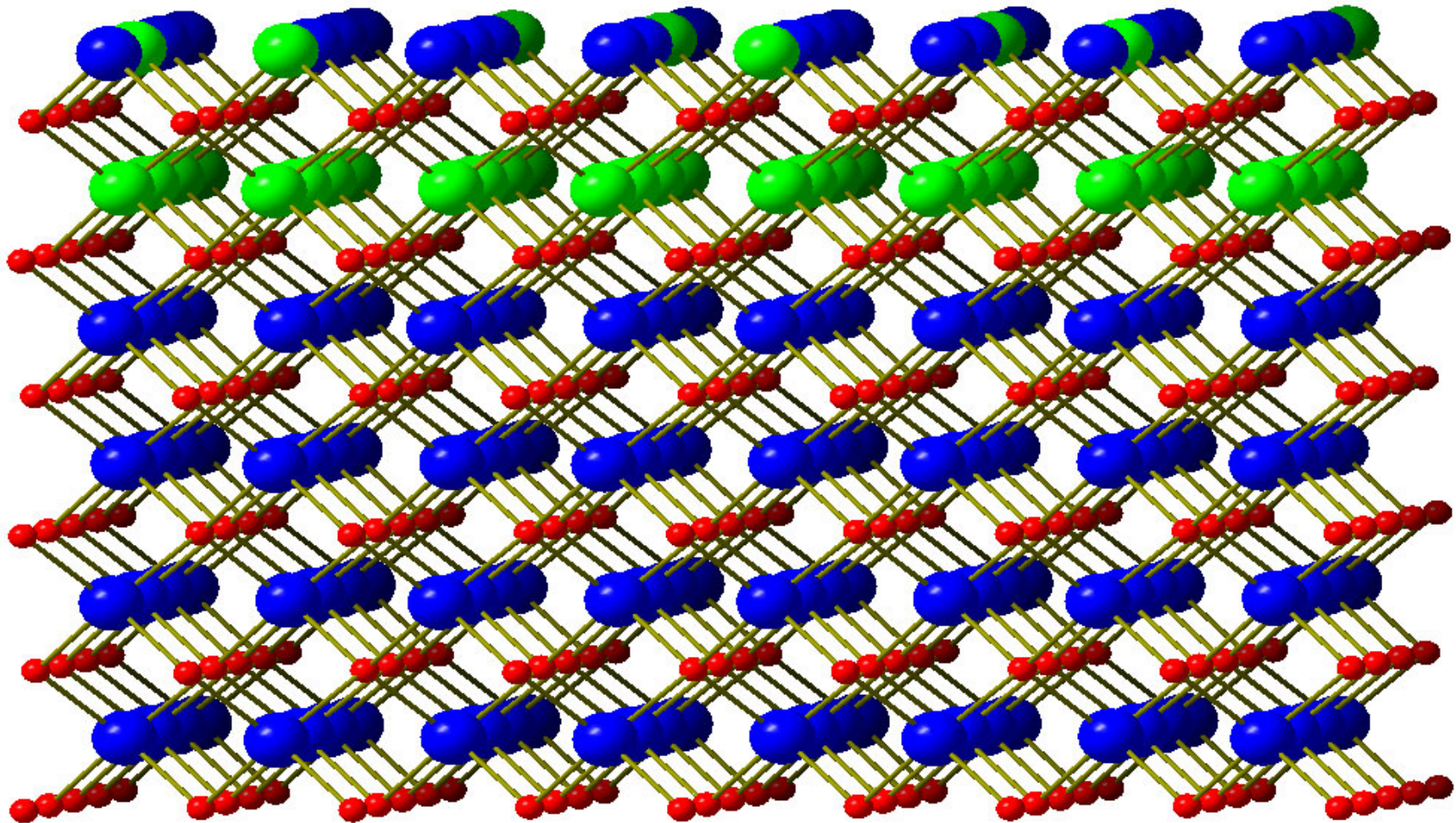
How do we create Bandgap Engineered Structures? Epitaxy



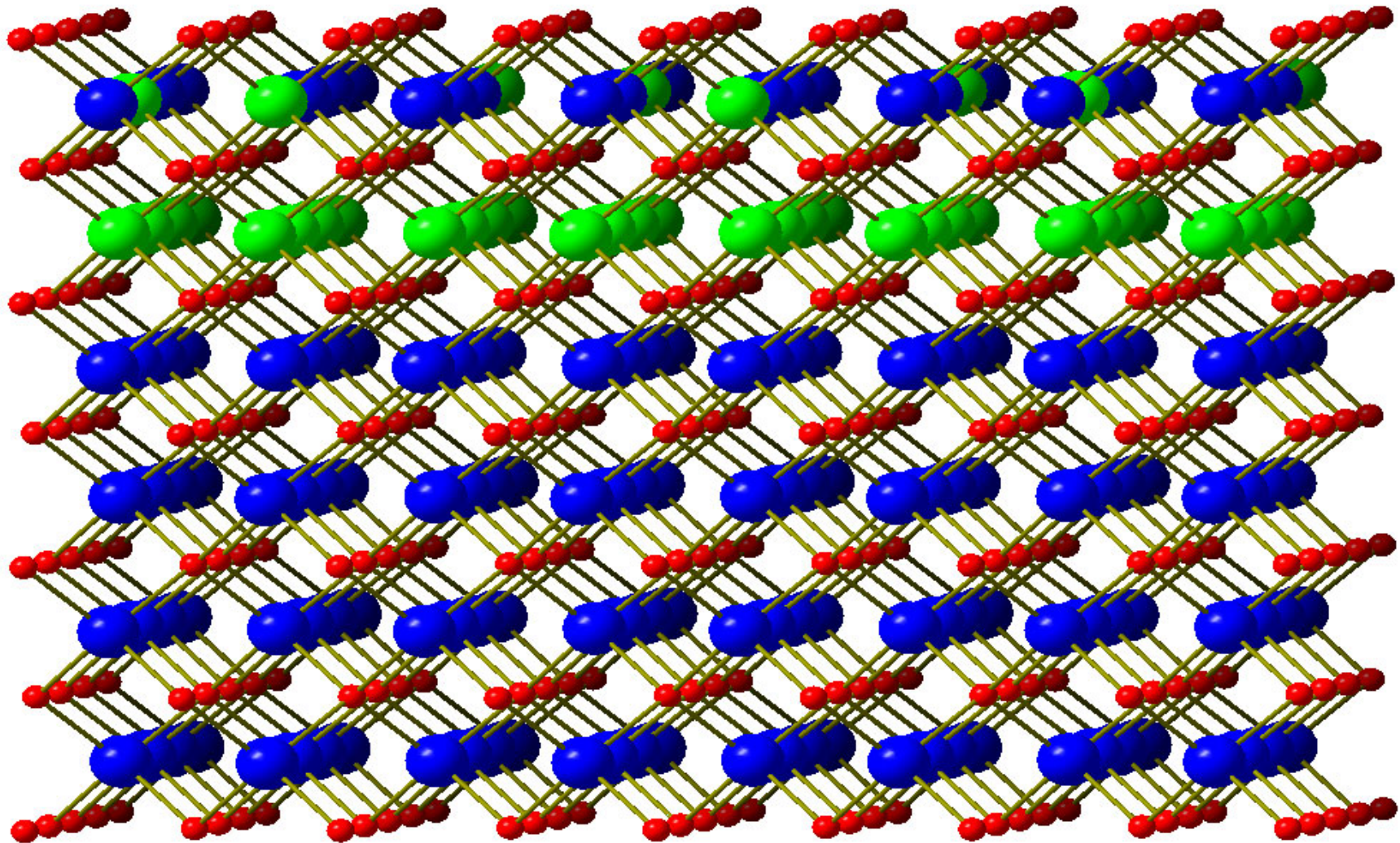
How do we create Bandgap Engineered Structures? Epitaxy



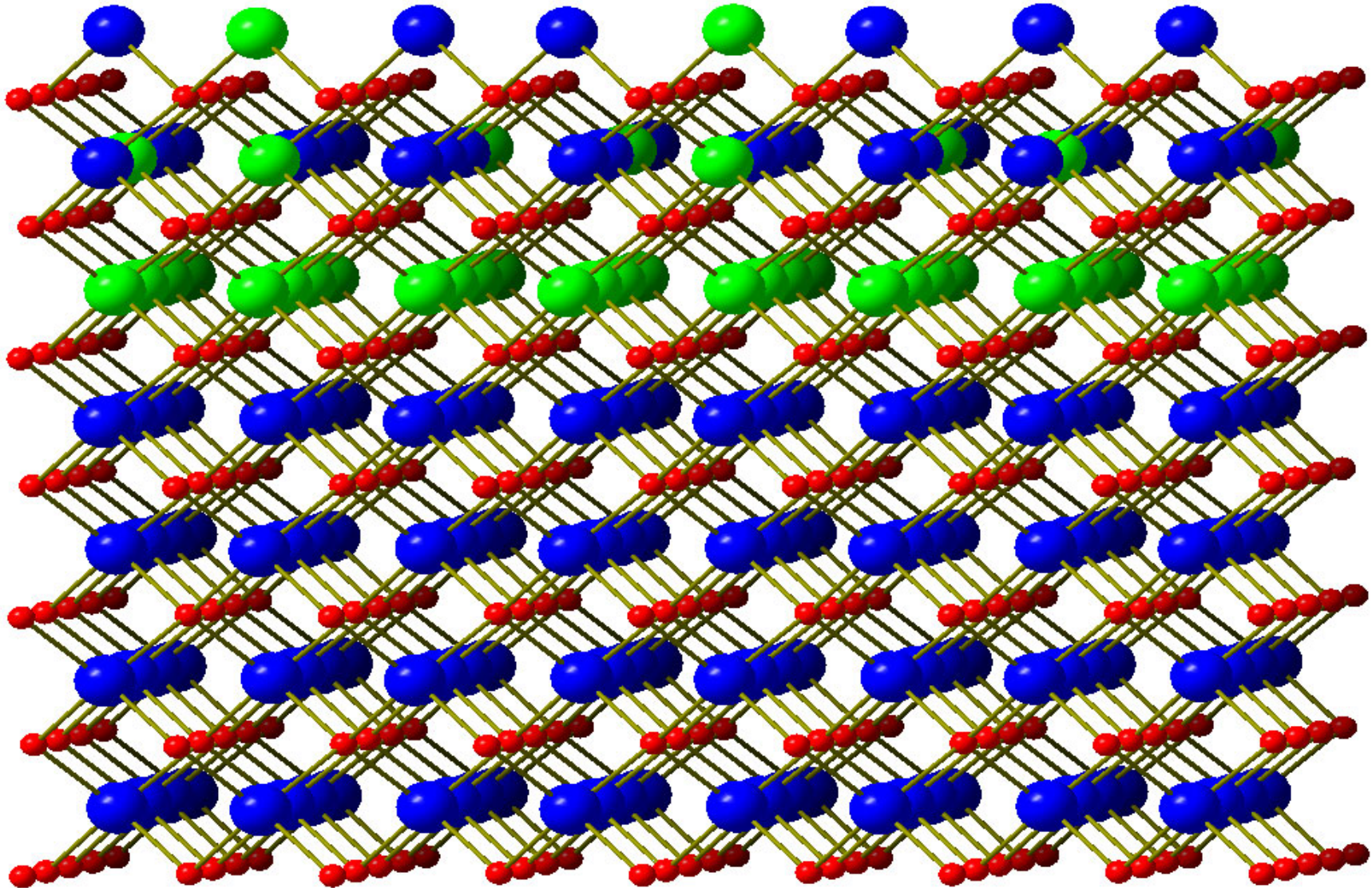
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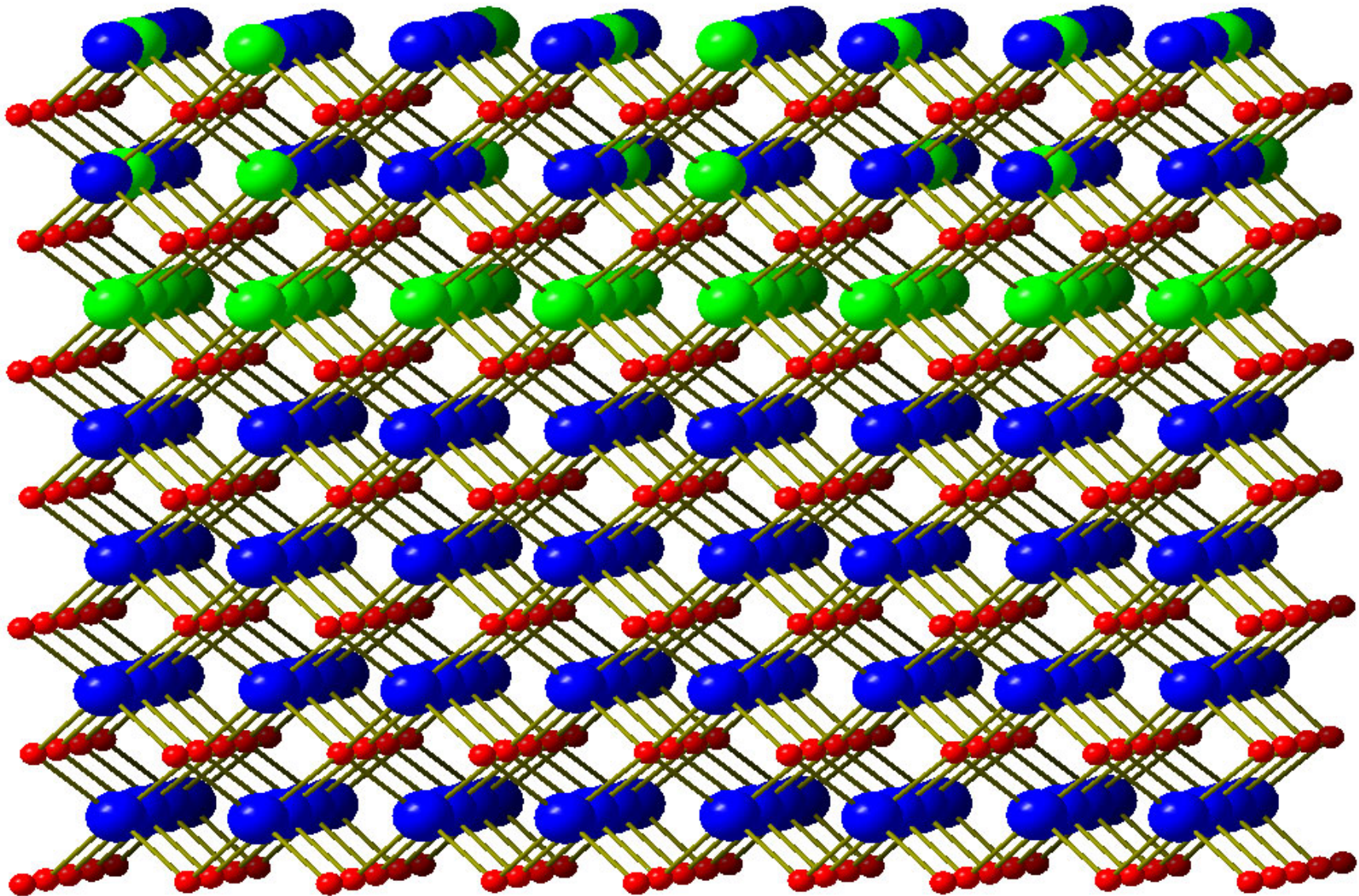
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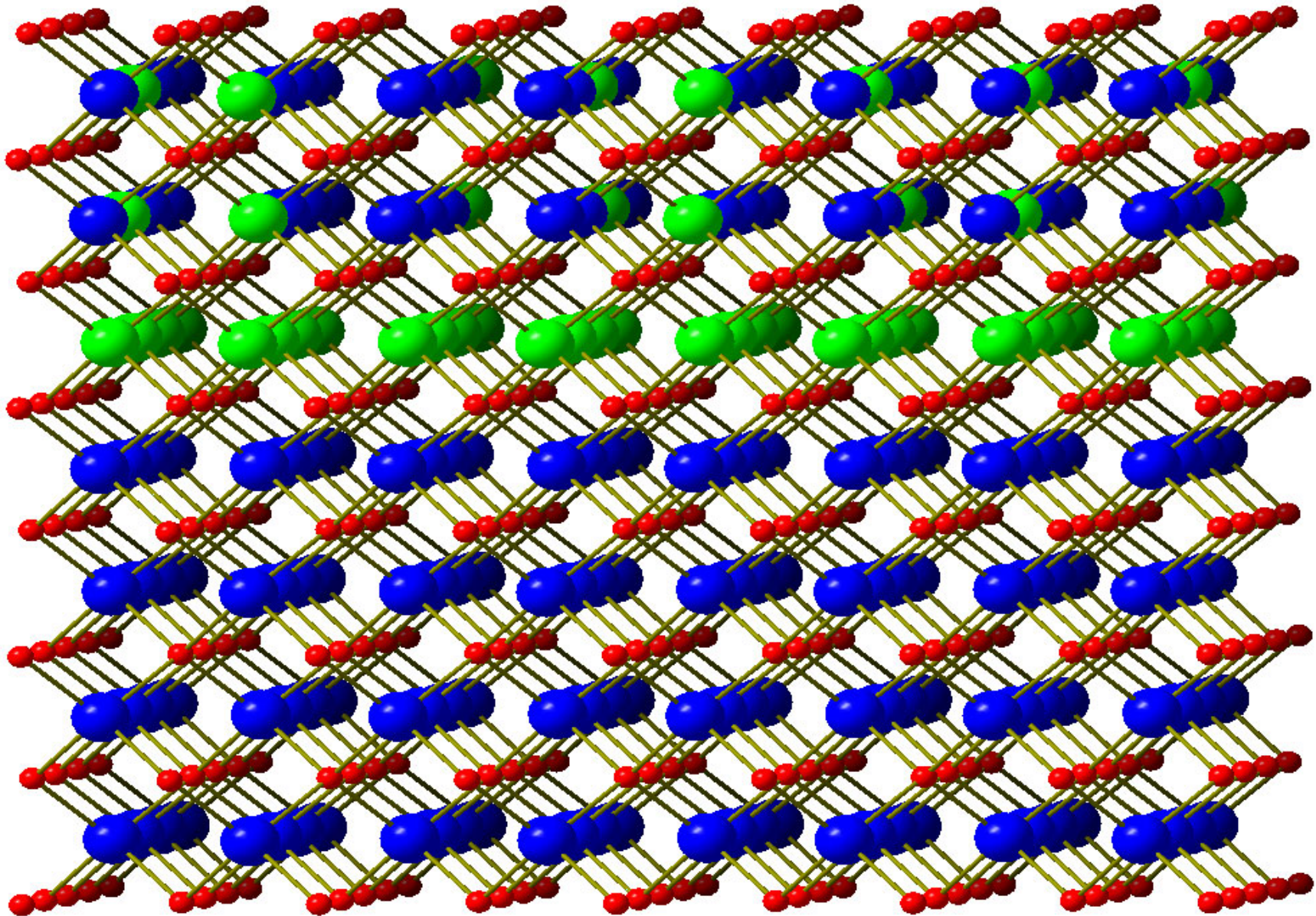
How do we create Bandgap Engineered Structures? Epitaxy



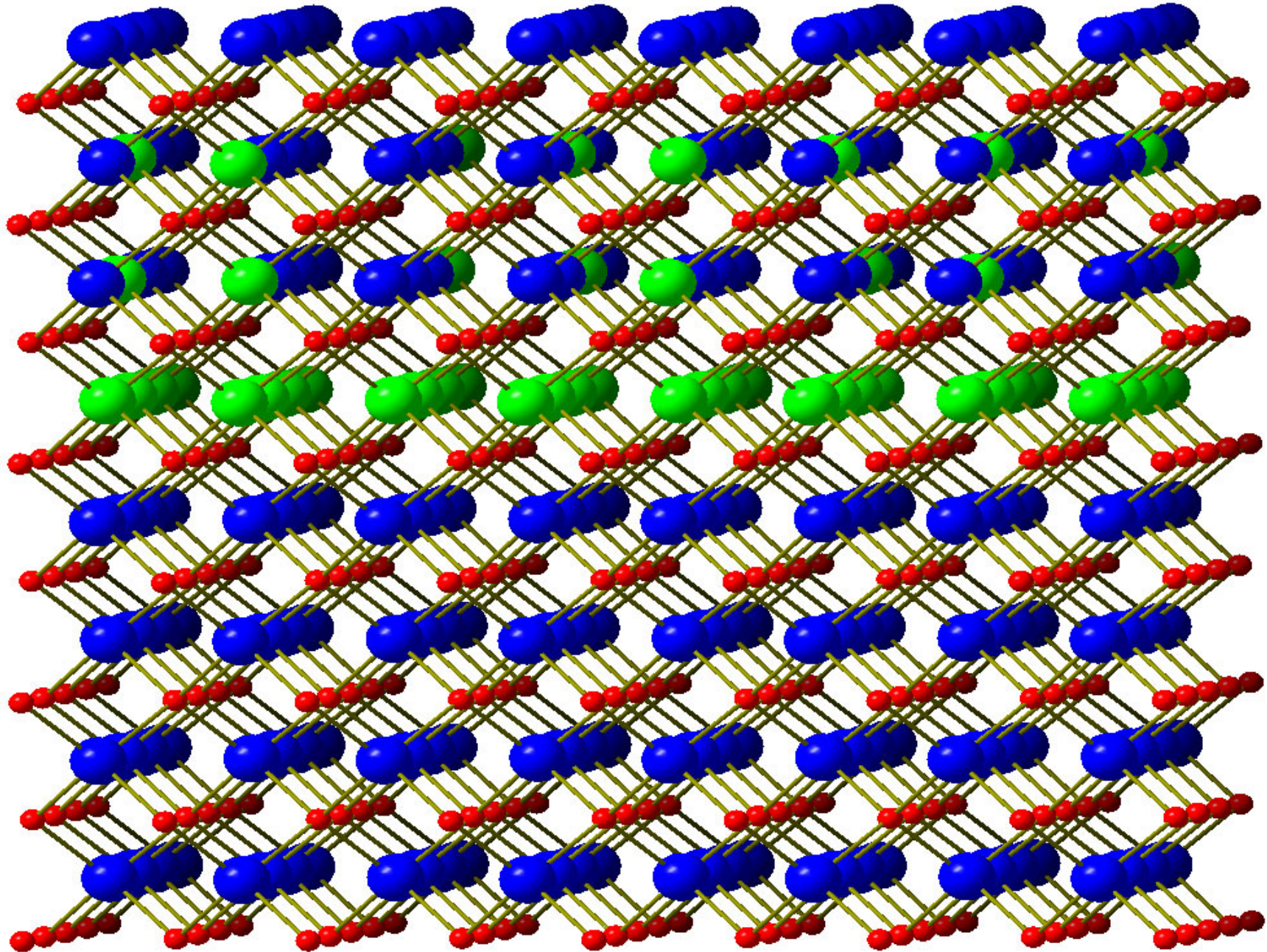
How do we create Bandgap Engineered Structures? Epitaxy



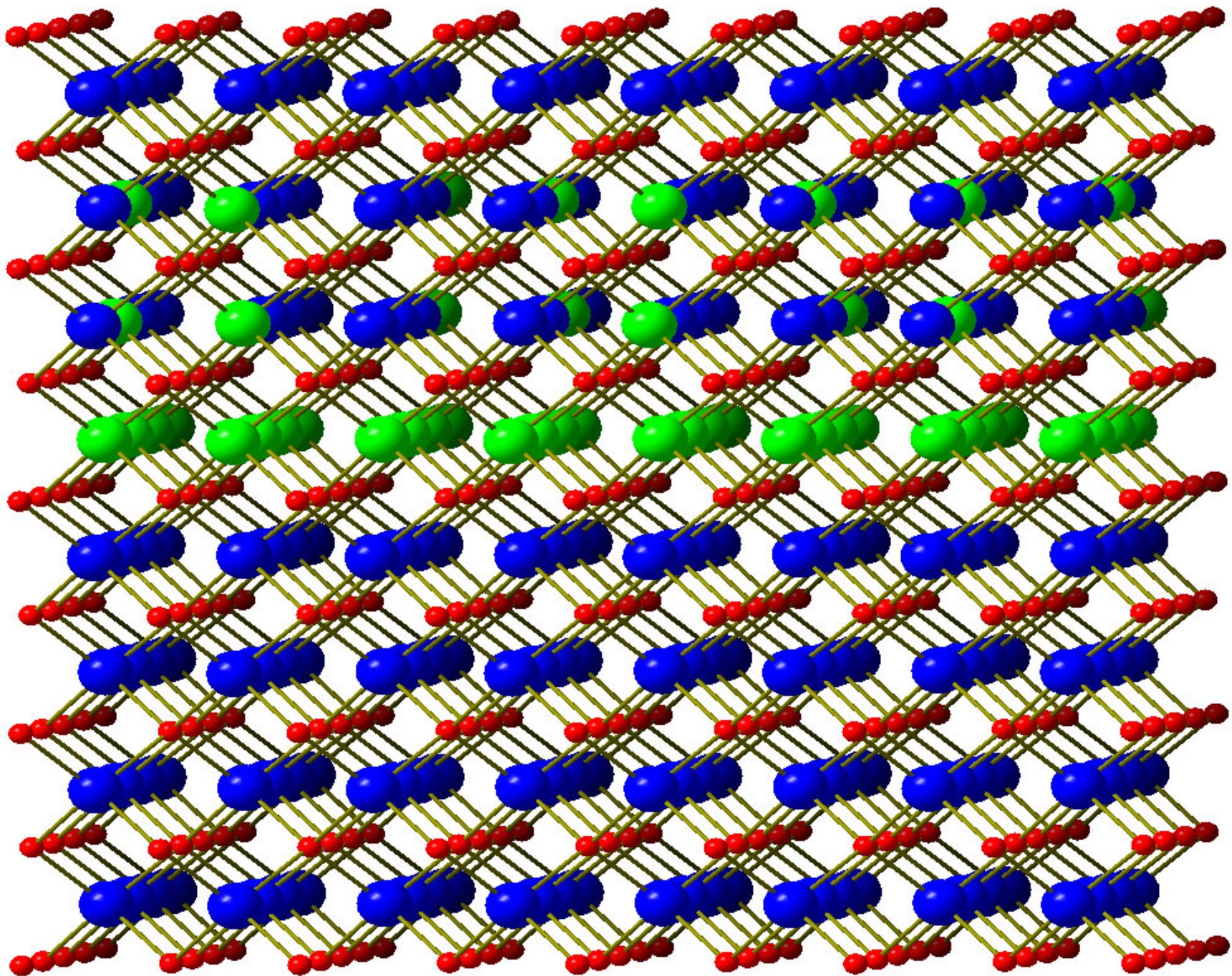
How do we create Bandgap Engineered Structures? Epitaxy



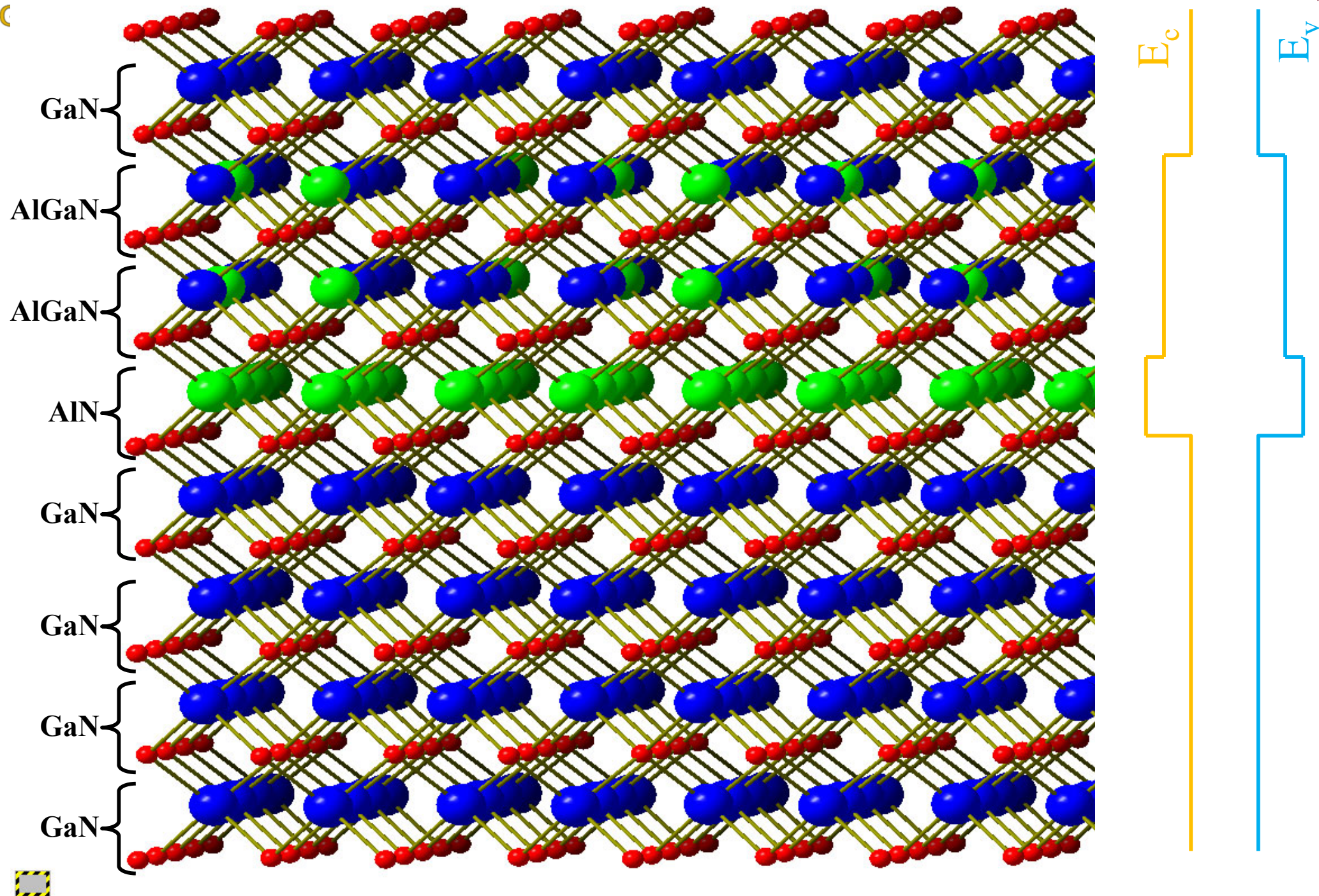
How do we create Bandgap Engineered Structures? Epitaxy

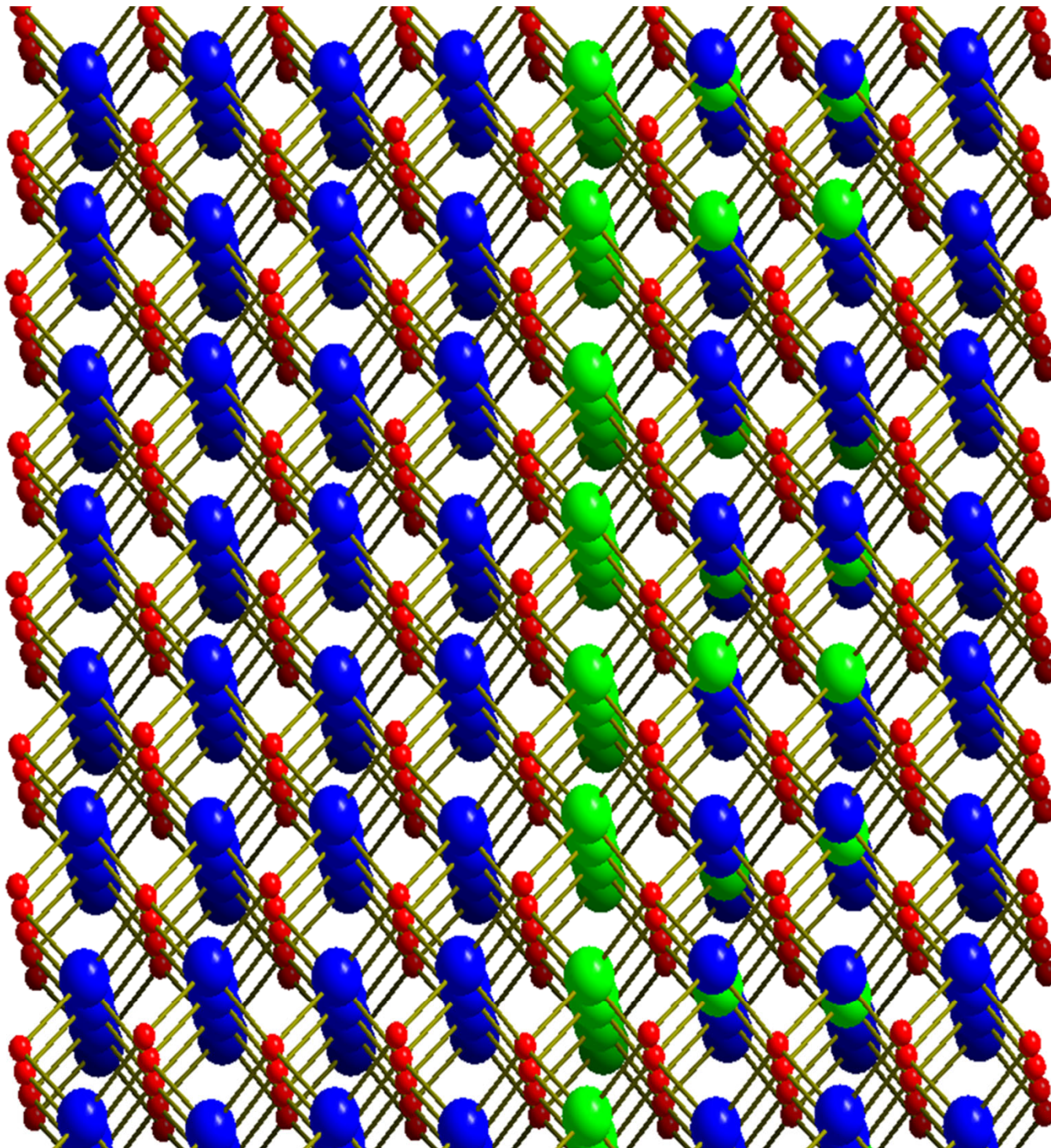


How do we create Bandgap Engineered Structures? Epitaxy

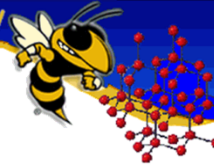


How do we create Bandgap Engineered Structures? Epitaxy





$$E_c$$



MBE

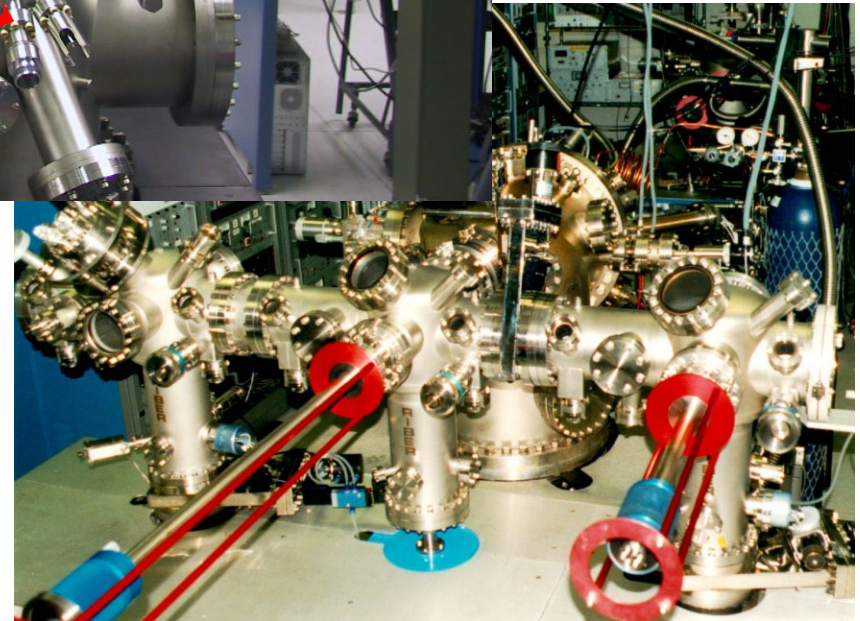
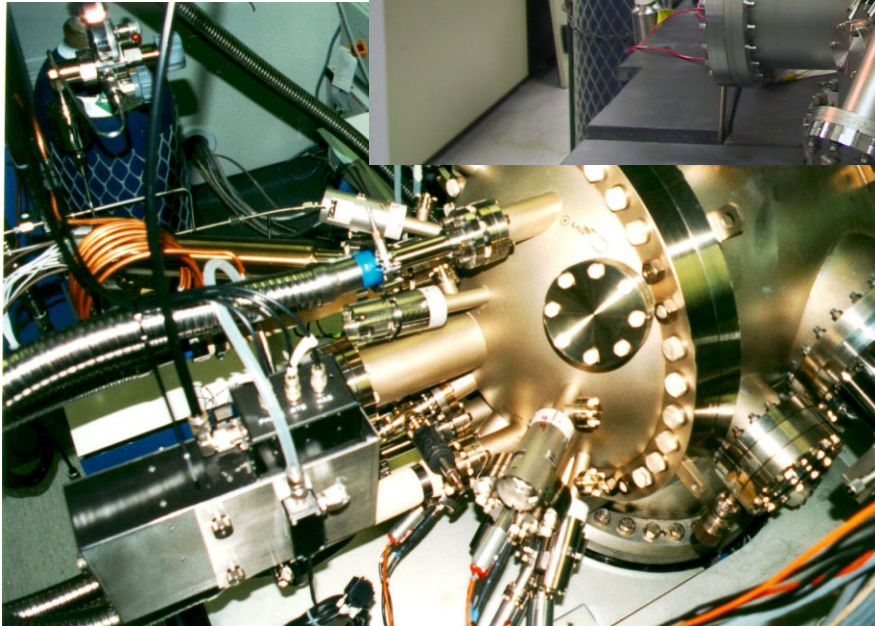
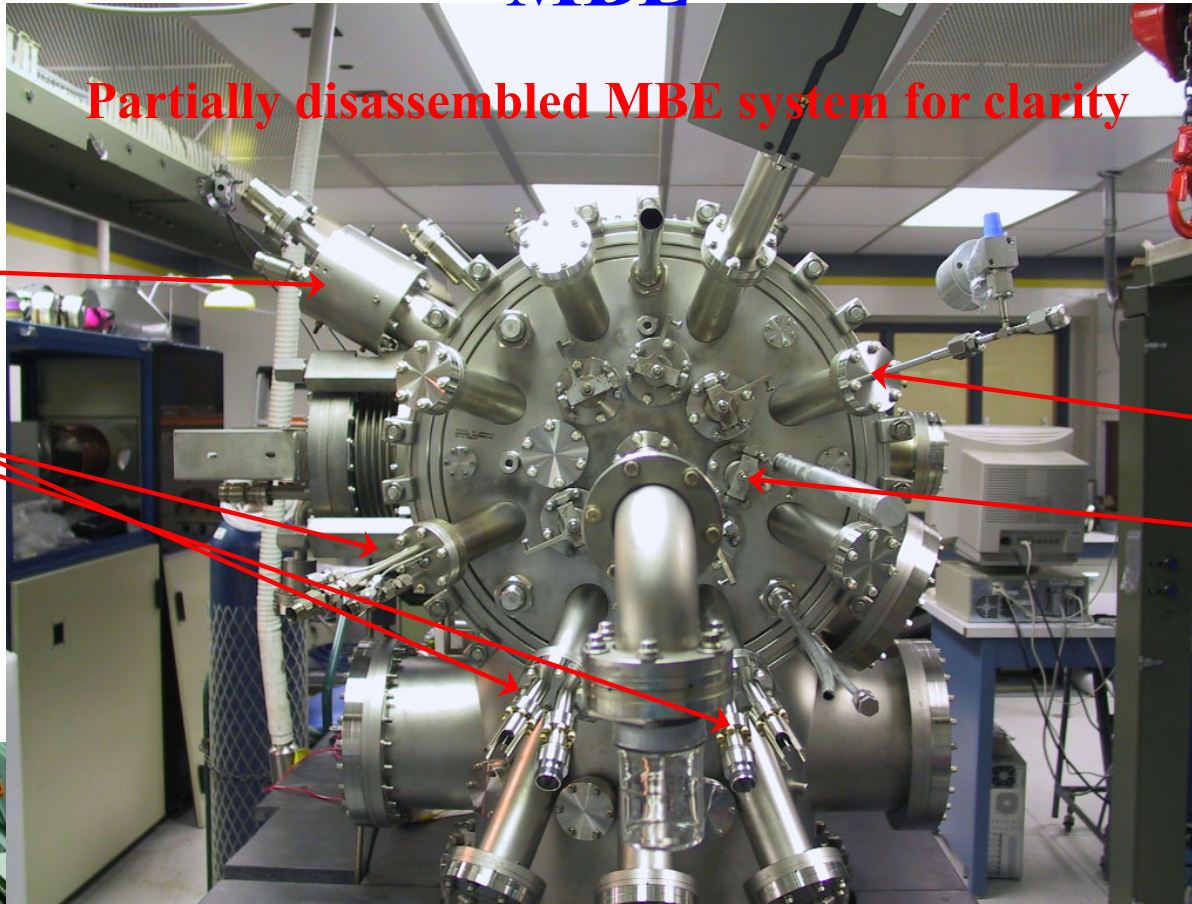
Partially disassembled MBE system for clarity

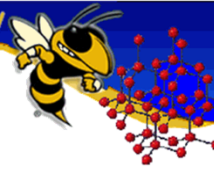
RHEED Gun

Effusion Furnaces

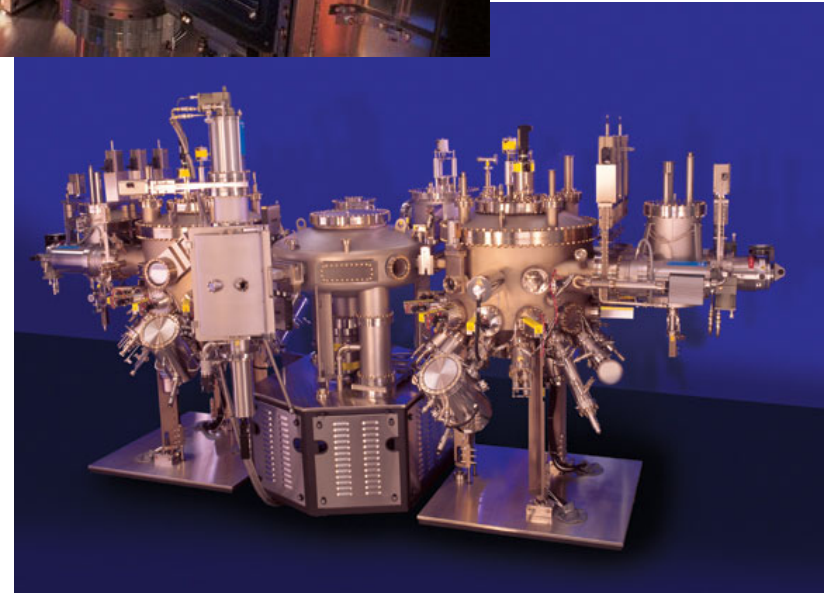
Gas Source (oxygen)

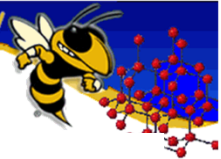
Shutter mechanism





Commercial Veeco® MBE





Alternative Methods: MOCVD

Primarily used for II-VI, and III-V semiconductors, special metallic oxides and metals.

Metal Organic Chemical Vapor Deposition (MOCVD)

- Many materials that we wish to deposit have very low vapor pressures and thus are difficult to transport via gases.
- One solution is to chemically attach the metal (Ga, Al, Cu, etc...) to an organic compound that has a very high vapor pressure. Organic compounds often have very high vapor pressure (for example, alcohol has a strong odor).
- The organic-metal bond is very weak and can be broken via thermal means on wafer, depositing the metal with the high vapor pressure organic being pumped away.
- Care must be taken to insure little of the organic byproducts are incorporated. Carbon contamination and unintentional Hydrogen incorporation are sometimes a problem.

Human Hazard: As the human body absorbs organic compounds very easily, the metal organics are very easily absorbed by humans. Once in the body, the weak metal-organic bond is easily broken, thus, poisoning the body with heavy metals that often can not be easily removed by normal bodily functions. In extreme cases, blood transfusion is the only solution (if caught in time). “Luckily”, such poisoning is rare as the pyrophoric (flammable in air) nature of most metal organic means the “victim” is burned severely before he/she can be contaminated.

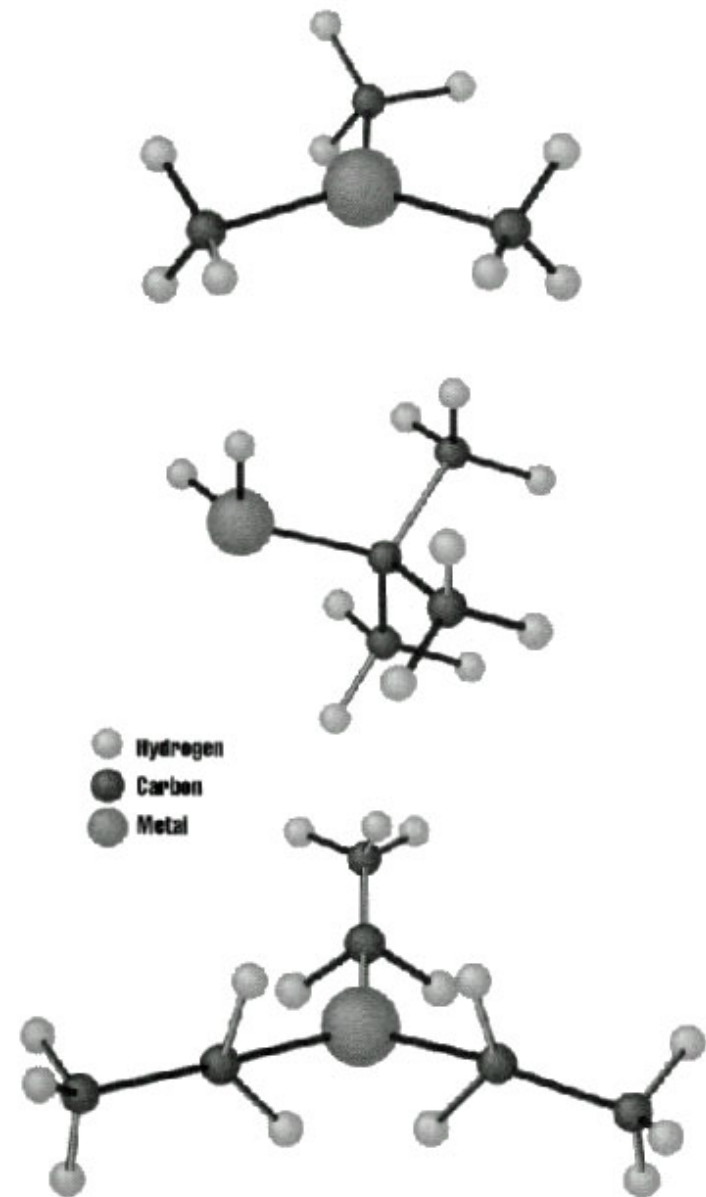
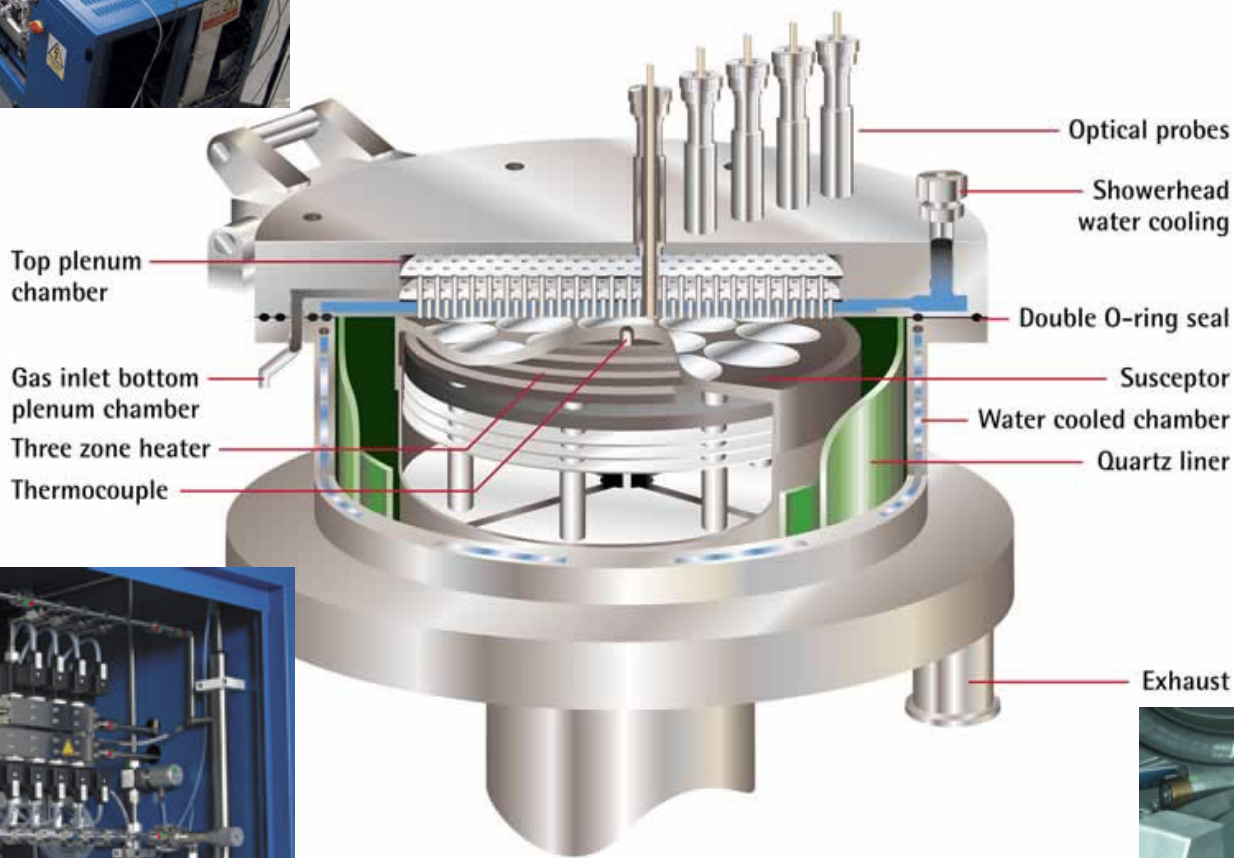
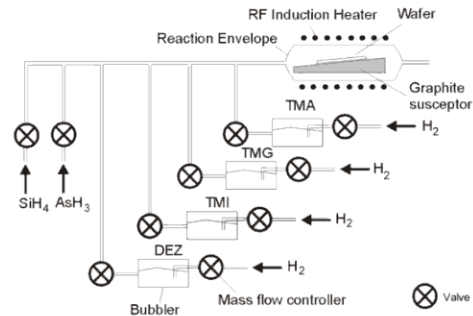
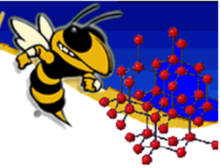


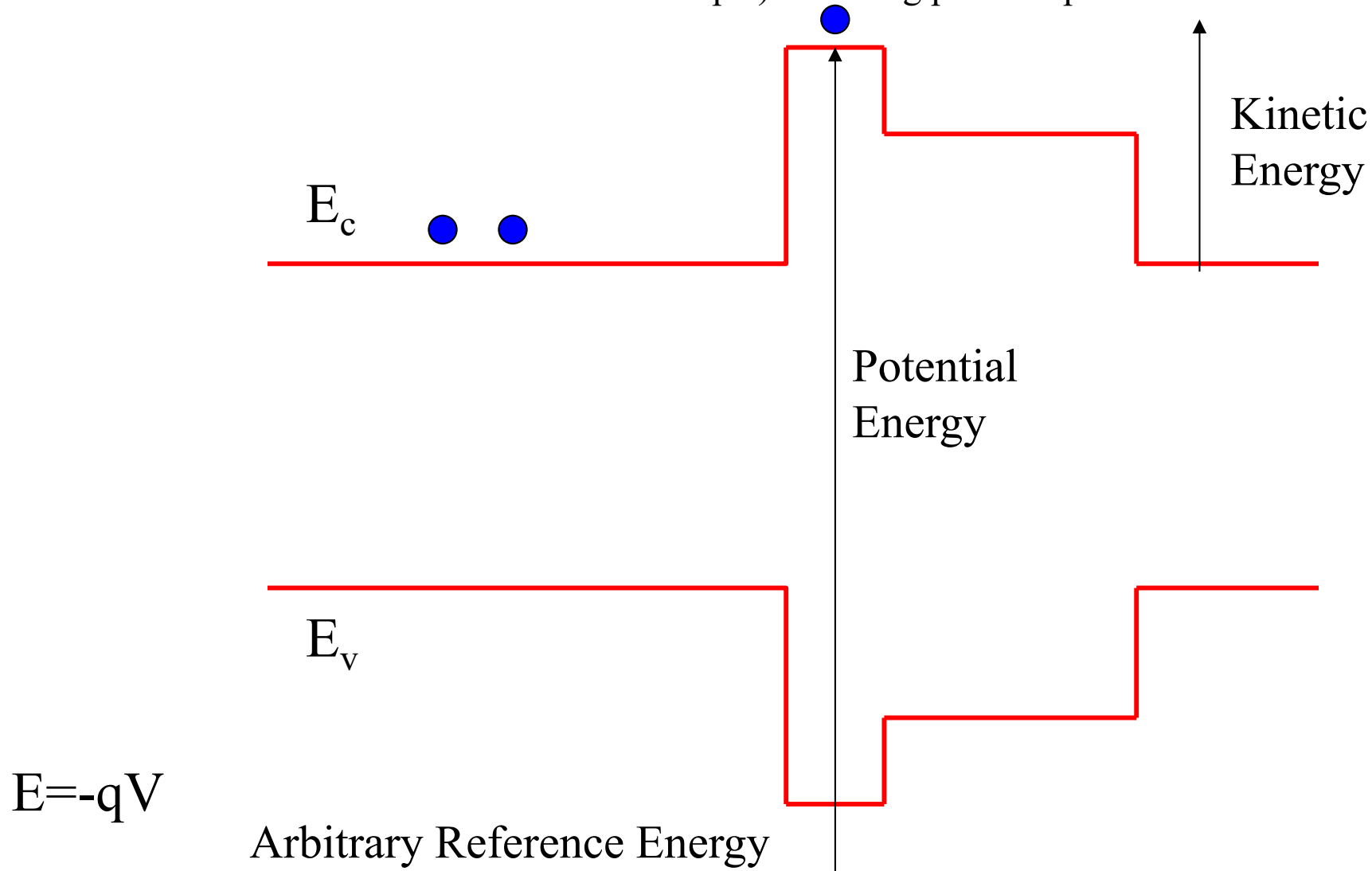
Figure 14-19 Examples of common organometallics used in MOCVD include (from top to bottom): trimethylgallium, tetrabutylarsine, and triethylgallium.

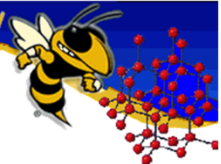




Engineered Energy Behavior in Compound Semiconductors

The potential distributions we will use in this class are all possible/common in device structures. Some may represent “grown in potentials” (quantum wells, etc...) or naturally occurring potentials (parabolic potentials often occur in nature – lattice vibrations for example) including periodic potentials such as lattice atoms.





**So much for the
introduction.
Now on to the
meat of the
course.**