CRYSTAL SETS TO SIDEBAND © Frank W. Harris 2022, REV 16

Chapter 4A HERTZIAN WAVES IN THE BASEMENT

Crystal set radios and ancient spark gap transmitters from the 19th century may seem too simple and too far removed from ham radio to be worth building. If you're already familiar with basic electronics and early radio history, you may not learn anything from this exercise. If you can't wait to build a real ham rig, please skip ahead to the next chapter. On the other hand, if you have little electronics experience, there are worlds of lessons to be learned from old technology. Or, if you've never built simple radios before, you might find it fun.

The nature of radio waves

Before we build transmitters and receivers, let's review radio waves. When we understand what radio waves are, the technology to generate and receive them becomes more obvious. An electromagnetic wave is an oscillation in free space that radiates in all directions away from its source at the speed of light. It is called *electromagnetic* because it is both electric field energy and magnetic field energy. The wave oscillates or alternates back and forth between these two forms of energy as it travels.

Propagating across vacuum

From our experiences with magnets and static electricity, it's hard to visualize how a magnetic or electric field can travel millions of miles across the vacuum of space. To us, these fields always seemed tightly localized around the device that generated them. How can a magnetic field exist isolated in a vacuum, perhaps even light years away from the nearest atom? Suppose we could somehow magically generate a magnetic field or an electric field in space, miles from the nearest object. Would the field just sit in space forever waiting for an object to pass by and be influenced by the field?

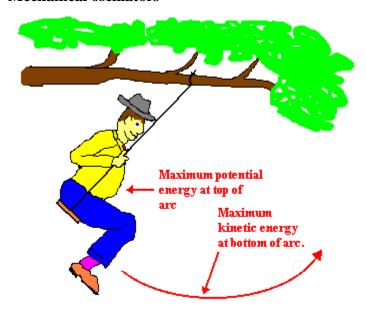
Static electric and magnetic fields are forces which project out into the space surrounding the battery or magnet that generated them. These forces are actual potential energy that exists outside the generator that produced them. The energy is confined locally because of the battery or magnet. Let's suppose there is a refrigerator magnet floating in the void of space: Its magnetic field will be at rest in the space surrounding the magnet, just as it does stuck to your refrigerator. As always, the magnetic field will reach out its usual distance of a quarter inch or so. However, if the magnet were to vanish suddenly, the energy in the field would lose its "container" or "anchor" and be turned loose in the void.

The same scenario can be proposed for an electric field: If a flashlight battery were floating in space, the electric force would extend perhaps an inch out into the space in a halo around the two battery terminals. Again, if the battery suddenly vanished, the electric field energy would lose its generator and be stranded in the void. Without its anchor, it would spill out in all directions. I like the analogy of a glass of water sitting on a table. If the glass suddenly shatters, the water will spill out in all directions.

Oscillation occurs when two forms of energy change back and forth rhythmically

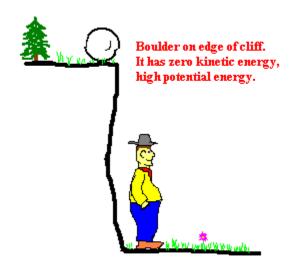
When magnetic and electric fields are turned loose in space, what becomes of them? As James Maxwell first explained over a century ago, electric fields and magnetic fields are intimately related. It turns out that *a changing or moving electric field generates a changing magnetic field and vice-versa*. As the energy continues to "spill" out in all directions, the energy oscillates back and forth between these two kinds of fields. This connection is not "obvious" or intuitive. If it were, the Egyptians, Greeks or Chinese would have described and exploited it long ago.

Mechanical oscillators



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Many physical devices in our world oscillate, so oscillation between electric and magnetic fields should not be a surprise. An oscillation in nature can be described as energy spontaneously transforming from one form of energy into another then back again. For example, as a clock pendulum swings back and forth, the pendulum acquires the kinetic energy of motion as it swings through the bottom of its arc. Then, when the pendulum swings back uphill, the energy contained in the kinetic energy is returned to gravitational potential energy. When the pendulum reaches the top of its swing, it momentarily comes to a complete halt, turns around and races back downhill. When it is at the top, the energy is all "potential." A boulder sitting on the edge of a cliff doesn't seem to have any energy until it is nudged off the cliff. The fellow standing at the bottom of cliff can testify that the rock has plenty of energy when it slams into the foot of the cliff. (That assumes, of course, that he survives.)



To reiterate, an oscillating pendulum switches its energy back and forth between kinetic energy and potential energy. Notice that the **length** of the pendulum establishes the oscillation frequency of a pendulum, not the weight of the pendulum. This is because gravity is constant and lightweight objects fall just as fast as heavy objects. If you ignore air resistance, the frequency of the pendulum swing is determined solely by the length of the pendulum arm (and of course the acceleration of gravity). This makes pendulums good for keeping a mechanical clock running uniformly and accurately. Similarly, once the frequency of a radio wave is established, big signals and small signals don't change frequency as they race through space and become weaker.

In summary, free space (which is literally "nothing"), can support magnetic or electric field energy, but only temporarily. To be maintained, a magnetic field needs to be generated by a device. A magnetic field can be generated temporarily by a nearby collapsing electric field. As the magnetic field collapses, it produces a temporary electric field in the adjacent space. This seesaw produces a radio wave traveling outward across the void at the speed of light.

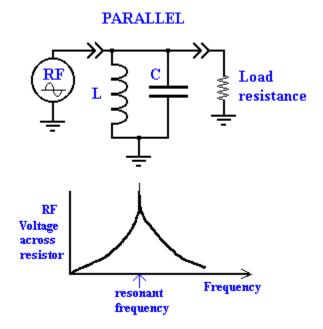
The speed of light

What's special about the speed of light? Good question! Einstein's laws of relativity teach us that time and space are frozen like a 4 dimensional ice cube. Most people are aware that light speed is the ultimate velocity. What is rarely understood is that *light speed is really "the speed of time itself."* Relativity is almost never studied deeply, even by engineers. This is perhaps because, until the invention of portable atomic clocks, the evidence proving that relativity was real was fragmentary and not very convincing. For example, when the first GPS satellite was launched, the software had "switches" that allowed ground engineers to turn off the adjustments for Special and General Relativity. They did this because they thought relativity might be wrong. Relativity was correct. The crazy theories turned out to be laws. Our universe is weird and profound far beyond what 99.9% of humans have the privilege to notice. However, these subjects belong in another book.

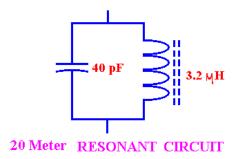
Getting back to 19th century radio: Transmitter antennas are designed to generate either a rapidly changing electric field, or alternatively, a rapidly changing magnetic field. The antenna is placed out in the open with free access to the sky. The changing electric or magnetic fields around the antenna create the opposite kind of field and the result is a free-flying radio wave. The

same antennas work well for receivers. As radio waves flash past the metal antenna elements, electric currents are induced into the structure just as if it were temporarily a capacitor or the secondary loop of a transformer.

The LC circuit, the fundamental electronic oscillator



The most fundamental component of all radio transmitters and receivers is the *capacitor/inductor parallel resonant circuit*. This basic circuit consists of an inductor wired in parallel with a capacitor. These are called *LC circuits* where L is the letter used when calculating inductance and C of course stands for capacitance. If a high frequency sinewave voltage is applied across the parallel LC circuit, there is a specific frequency at which the LC circuit resonates and appears to be an open circuit. At all the other frequencies the LC appears as a load or short circuit. The LC circuit attenuates or eliminates the sinewave at every frequency except one. In this way one radio signal can be "tuned in" preferentially over another.



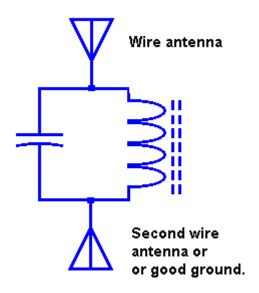
For example, the circuit above resonates at 14 MHz, the 20-meter hamband. The tiny inductor is just 3.2 microHenries. The capacitor is only 40 picoFarads which means 40 millionths-of-a-millionth of a Farad.

The LC circuit is a kind of electric oscillator. It is analogous to a swinging pendulum or a

weight bouncing up and down on a mechanical spring. The LC oscillator goes through the same energy cycle as radio waves. First the energy is stored in the magnetic field inside and around the inductor. During the next half cycle, the energy is stored in an electric field between the plates of the capacitor. The energy alternates back and forth between these components until the resistance in the wires dissipates it.

A parallel resonant LC circuit with dual antennas forms a simple transmitter

Significant energy can also be leaked off into the space around the LC circuit as radio waves. Therefore, once we are able to make an LC circuit oscillate, we are on our way to generating radio waves. *If we simply add wires to the ends of the parallel LC circuit, these wires form an antenna to couple the electric field to the free space around it.* In other words, the simple circuit shown below is a crude radio transmitter.



A receiver of radio waves can be built in the same way. Imagine that an identical parallel LC circuit with antennas is tuned to resonate at the same frequency. Now imagine that this second circuit is floating in the void, perhaps miles from the transmitting circuit. When the radio waves radiate past the receiving LC circuit, the electric field component in the radio wave will produce a tiny surge of current in the wires that charge the capacitor. Alternatively, and depending on the orientation of the coil with respect to the radio waves, the magnetic component of the radio wave will induce a tiny voltage to appear across the coil. This is the same as if the inductor were the secondary of a transformer. Once the radio wave has zoomed past, a tiny, miniscule oscillation will remain in the receiving LC circuit, ringing back and forth between the inductor and capacitor.

I bought a book at a local bookstore. Since I bought it to give as a birthday gift, I cut off the price label. The label was a tough multiple-layered device of plastic, paper and foil. I peeled it apart and discovered an LC "receiver" just like the diagram above. The capacitor was 2 small squares of foil separated by a thin layer of plastic. The inductor was a spiral of foil printed on a sheet of thin plastic. If I had attempted to leave the store without paying, a transmitter at the door would have resonated with the receiver and set off an alarm.

CRYSTAL SET RADIOS

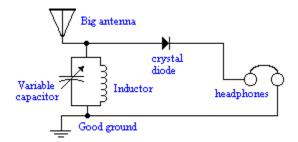
A crystal set is an excellent first electronic project. They have few parts and are easy to understand and build. Crystal sets were a common toy when I was a kid. The set below belonged to my brother-in-law, Peter Hill, and probably dates from roughly 1940. I discovered it collecting dust in the attic.





I connected the set to an antenna and ground. No matter how I adjusted it, it was as silent as the attic it came from. A "crystal" usually consists of a tiny piece of lead-sulfide crystalline ore imbedded in a small cylinder of solder. To my amazement, there was also a spare crystal in its original little box. The spare was manufactured by the Clearco Crystal Company in Idaho Springs, Colorado. The town is located in a canyon on Clear Creek. Idaho Springs is a gold and silver mining town that had its boom time in the late 19th century. By the 1930s, Idaho Springs was nearly a ghost town. The silver ore was a mixture of several metal-sulfides, primarily lead-sulfide. The crystal is labeled "galena" which is the common name for lead-sulfide. It is almost certainly the local ore and works as well as pure galena. Notice that they call their crystal "the silver tone." The existence of this little company during the Great Depression is a tribute to those creative fellows who found a way to make a living during a grim time for Colorado miners. I installed the replacement crystal in the set but it remained silent. I happened to press the earphone hard against my ear and heard a faint station. The tuning was surprisingly sharp, but it wasn't nearly loud enough. For now I'll allow this historic radio to rest in peace.

As you might expect, my first electronic project was building a crystal set. Although we kids played with crystal sets, we didn't understand them. When they didn't work, we had only the haziest notion of how to fix them. I never saw a commercial toy crystal set that had explanations even remotely as complete as what you are now reading. Starting with crystal set theory, we can build on these concepts to build transmitters and more elaborate receivers.



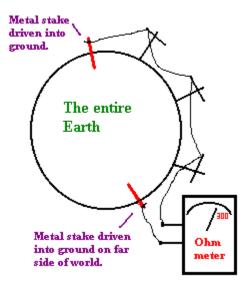
The combination of inductor and capacitor tune in the desired station. That is, the inductor and capacitor oscillate at the frequency of the desired station. The crystal diode rectifies the sinewaves oscillating across the LC circuit. "Rectification" clips off one polarity of the radio frequency, alternating polarity sinewaves. This converts the high frequency sinewaves into low frequency DC - direct current - which varies at sound wave frequencies. The earphone has too much inductance to pass radio waves, but does admit low frequencies that can be turned into low frequency voice and music. The magnet and coil in the headphones cause a steel diaphragm to vibrate, generating the sound. Crystal sets have six basic parts. The antenna of course picks up the signal from the air.

The antenna

For crystal sets it is easiest to build an "electric field" antenna. It is usually just a long piece of wire strung out a window or up in a tree. A limitation of a single wire antenna like this is that, when the radio wave generates a voltage on the wire, the current it might produce has nowhere to go. A simple wire antenna is like one terminal of battery. Yes, the battery has a voltage, but without a connection to the other terminal of the LC circuit, the current has no circuit to flow through. To provide a destination for the current we can add a second antenna. Alternatively we can connect the crystal set to "ground."

The ground

Electrical "ground" is a word that we learn as youngsters, but most people go through their whole lives without ever understanding it. I suspect that the term arose during the early days of telegraph communication in the 1840s. It turns out that wet earth is a fairly good conductor. If you drive two metal stakes into the ground in your backyard and connect a battery to the two stakes, current will flow from one stake to the other. For two stakes about 100 feet apart, the ground has a resistance of about 100 ohms. If you experiment, you learn that most of the electrical resistance to current flow occurs right around the stakes. Once the current gets launched, the electrical resistance only increases slightly as you increase the distance. A metal stake in a backyard in China and one in a backyard in the U.S.A. might only have 300 ohms resistance between them. This was a boon for early telegraphers because it meant they only had to string one wire between cities instead of two wires to complete the circuit loop. In practice, using ground as an intercity "wire" is not as reliable as stringing a second wire, but it illustrates the concept of ground.

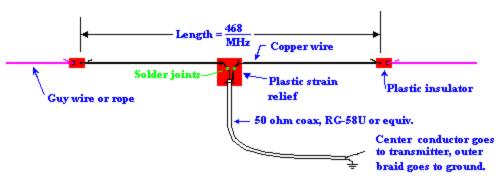


A good electrical connection with ground is an essential component of the crystal set. The most accessible ground for a crystal set or a ham radio station is usually a copper water pipe or a hot water heating pipe. At low Radio Frequencies, such as standard broadcast AM radio, ideal electric antennas are very large. Needless to say, being able to use the entire Earth as half of the antenna is often quite convenient.

Dipoles

Unlike low frequencies, for high frequencies, like VHF television or FM radio, the ideal length for an electric antenna is just a meter or so. The higher the frequency, the less distance there is between successive electric and magnetic propagating waves. That is, the wavelength decreases with increasing frequency.

Although in theory you could use a stake driven into your lawn for the "ground" path return for your TV, it is much simpler just to use a second short antenna oriented 180° away from the "real" antenna. This dual antenna is called a *dipole* and is the most common basic antenna design used in ham radio and TV antennas. Although it isn't obvious, the arrays of thin aluminum tubes on rooftop TV antennas are just refinements of the basic dipole antenna. In general, the lower the frequency, the larger the dipole must be in order to work well. A typical ham radio dipole is shown below.

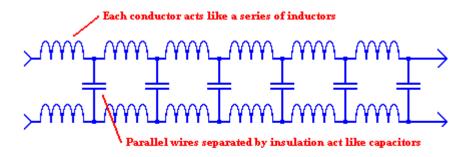


For 40 meters the length is 66 feet. The coax feed line can be any length, but shorter is better.

Transmission lines

In the ham radio dipole antenna above, the "arms" stick out in space in opposite directions and snag the passing electrical field. In general, the higher the dipole is above the local terrain, the better the dipole will receive signals. Unfortunately, you and your radio are down on the ground. Climbing up on the roof to listen to the radio or watch TV is inconvenient, to say the least. A *transmission line* solves the problem of how to move radio frequency signals down to a receiver or up from a transmitter.

A transmission line is a pair of parallel wires separated by insulation. It works very much like a speaking tube in a ship or even the string in a tin can telephone. In all these devices, vibrations are transmitted down a narrow pathway with surprisingly little loss of energy. A terrific example of a mechanical transmission line can be a farmer's ditch filled with water. Provided the water is flowing slowly, when you throw a big rock into the ditch, the wave from the splash will travel hundreds of feet before it dissipates. A wave in the ditch propagates unchanged for many minutes and travels great distances. In contrast, if you throw the same rock into an open pond, the wave spreads out in all directions and quickly vanishes.



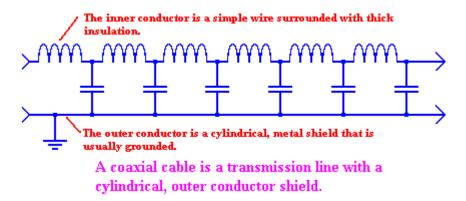
Two parallel wires separated by insulation make up a transmisison line.

A radio transmission line is a distributed, LC resonant circuit. We saw in Chapter 2 that a simple wire has inductance. Similarly any two wires separated by an insulator comprise a capacitor, whether we planned on making a capacitor or not. Consequently, when we run two parallel, insulated wires over any distance, there will be a measurable capacitance between them and the wires themselves will have a significant amount of inductance. To a radio wave, this

construction looks like a long, continuous LC circuit. As the capacitance and inductance are charged and discharged, the oscillation doesn't stand still, but rather moves down the pair of wires at nearly the speed of light. As you can see, propagation down a transmission line is analogous to propagation through free space, but it only propagates in one dimension instead of three dimensions. The electric field or voltage generates a current and magnetic field, which in turn generates a new electric field and so on. An example of a simple transmission line consisting of two parallel wires is the flat wire "300 ohm" twin lead used to feed older TVs.

Coaxial cable

The round, shielded transmission line used to feed modern TVs is a *coaxial cable*. Instead of using two separate ordinary wires, the outer conductor of a coaxial cable is a metal cylinder that completely encloses the center conductor. The inductance of the shield conductor is far less than that of a simple wire, but it prevents the radio frequency signals on the inner conductor from leaking out. Even better, it shields new signals from leaking into the cable and interfering with TV reception.



The ham radio dipole antenna described earlier uses type RG-58 coaxial cable to transport the radio frequency signals down into the house. You will notice that the outer shield is connected to ground. This is nearly always the case with coax. You could use cheap TV coax cable for your ham transmitter, but you will find it difficult to work with. The outer shield of inexpensive coax is just aluminum foil and is difficult to connect mechanically and electrically. In contrast, the outer shield of quality coax is braided copper wire that is easy to cut and solder. It also has considerable mechanical strength.

Transmission line "characteristic impedance"

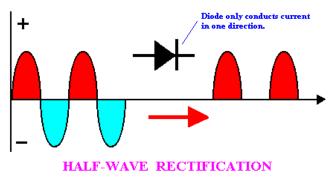
An abstract characteristic of transmission lines is that, from the point of view of a traveling radio signal, the line "looks like" a specific load resistance. For example, RG-58 coax appears to the radio signal to be a 50 ohm resistor. It isn't, of course, but the voltage and current levels along the wire suggest that it is. In other words, voltage divided by current at points along the line will give 50 ohms. Another reason not to use TV cable is that TV cable is usually designed for 75 ohms, while most ham equipment is designed for 50 ohms. Actually, the difference in performance would be minimal.

The old flat, brown, TV lead-in wire had a characteristic impedance of 300 ohms. In general, the finer the wire and farther apart the two conductors of a transmission line, the higher

the characteristic impedance. Sometimes hams use a wide "ladder line" in which bare copper conductors are separated by an inch or more of air and ceramic separators that maintain the distance between the wires. Ladder line often has an impedance of 600 ohms. Ladder line is useful when transmitter power must be transmitted great distances to get to the antenna. Because a ladder line has little or no insulation in contact with the wires, the small dissipation of energy in the insulation is reduced to the absolute minimum. More importantly, the high impedance means that smaller currents will flow in the wire and less energy will be dissipated in the resistance of the copper. Of course the trade off is that higher voltages are needed to transmit the same power levels. I know a ham who lives at the bottom of a canyon where radio reception is poor. He uses a long ladder line hung in the trees to connect his transmitter to the antenna which is located hundreds of yards up on the mountainside.

Diode detectors

The diode is the *detector* that converts radio frequency sinewaves into audio frequency electric waves, ready to be converted into sound. The diode is a "one way electricity valve." In plumbing terms, it works like a check valve. The schematic symbol for a diode is an arrowhead pointed at a barrier at right angles to the wire.



(Only one half of wave is exploited.)

In electronics, the convention for "positive" current flow is from positive to negative. Unfortunately, the flow of electrons is from negative to positive. So, what is actually "flowing" from positive to negative is the <u>absence</u> of electrons. Confusing, no? I suspect this convention was established before electrons were understood. Referring to the symbol for a diode, positive current is allowed to pass if it flows in the direction of the arrowhead. Positive current will be blocked by the diode if it attempts to enter the diode from the perpendicular "barrier" side.

Semiconductors usually perform the check-valve function of diodes. A semiconductor is a crystal of an element like silicon or germanium that has a chemical valence of 4. That is, during chemical reactions this element can either take up 4 electrons, or give away 4 electrons. When atoms react with each other to form a molecule, they share these outer electrons to form a stable outer "shell" of electrons. For most pure atomic elements, this outer stable shell needs 8 electrons to be stable.

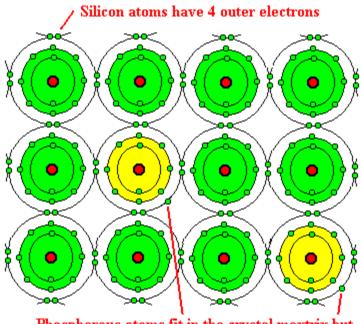
Extreme examples of stable elements are the inert gases; neon, xenon and radon. These atoms already have 8 electrons in their outer shells. For all practical purposes, these gases are totally inert and will not react with other elements to form molecules. As we shall see shortly,

semiconductors can also be fashioned by making crystals out of elements with either 4 outer electrons or mixed elements with valences of 3 and 5, or even 2 and 6. Notice that the valences of the mixtures still add up to 8 electrons.

N-type semiconductors

To keep it simple, let's suppose we have a pure crystal made out of silicon semiconductor, which has a "*valence*" of 4. The valence is the number of electrons loose enough to become bound to other atoms in a molecule. If we put some multimeter (ohm meter) probes across pure silicon, it will act like an insulator. There will be no significant current flow. The valences of pure silicon atoms in a crystal add up to 8 electrons because each silicon atom is sharing electrons with 4 other atoms so they all experience stable 8 electron outer shells.

However, if we make a new silicon crystal with just a touch of phosphorus impurity in it, suddenly the crystal becomes a conductor. Phosphorus has a valence of 5 and is almost the same as silicon in atomic weight. This means that in chemical reactions phosphorus normally accepts 3 electrons to complete an outer shell of 8 electrons. But when silicon crystal is contaminated with phosphorus, lone atoms of phosphorus are trapped among a frozen, rigid crystal of silicon. The phosphorus atom fits in the matrix, but it has an extra electron that is "loose" and free to move around the crystal. The electron can't move over to silicon atoms because they are joined with neighboring silicon atoms so that each silicon atom has a stable outer shell of eight shared electrons. However, the extra phosphorous electron can move over to other phosphorous atoms that have already lost their 5th electron. In other words, *a silicon crystal with just a touch of valence 5 impurity acts like metal*. It has electrons that are free to migrate through the whole solid. A semiconductor with extra electrons is called an *N-type semiconductor*.



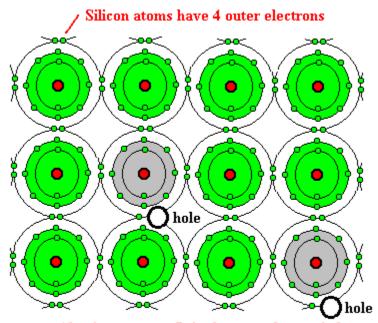
Phosphorous atoms fit in the crystal maxtrix but have 5 electrons in the outer electron shell.

N- TYPE SEMICONDUCTOR

P-type semiconductor

P-type semiconductor is a bit abstract. Instead of making a silicon crystal with valence 5 impurity, now suppose we add an impurity such as aluminum, indium or gallium with a valence of 3. The impurity fits into the crystal matrix, but it needs one more electron to reach an equilibrium of 8 electrons shared with its neighboring silicon atoms. In other words, this semiconductor has "holes" in the crystal matrix that can be filled by electrons passing through. Now when you place multimeter probes across a P-semiconductor, it will conduct just like the N-type semiconductor. However, the conduction mechanism is different. With P-type semiconductor, the negative metal probe touching the crystal supplies all the free electrons flowing through the crystal. These electrons are hopping from hole to hole to cross the crystal.

Like phosphorus, aluminum atoms have almost the same atomic weight and size as silicon. Aluminum atoms fit perfectly in the silicon crystal matrix.

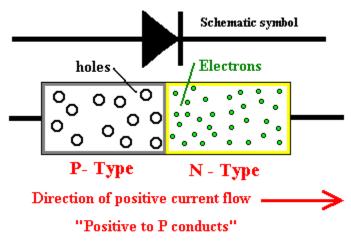


Aluminum atoms fit in the crystal maxtrix but have 3 electrons in the outer electron shell.

P - TYPE SEMICONDUCTOR

Diodes are P-N junctions

Semiconductor diodes are constructed by placing P- type semiconductor in contact with N-type semiconductor. In other words, for electrons to flow through the diode, the electrons must enter the N-type crystal and then move across the junction into the P-type where they complete the journey by jumping from hole to hole.



P-N SEMICONDUCTOR DIODE

"positive to P conducts"

If we measure the resistance across a diode with an ohmmeter, the resistance is low when we place the positive pole of the meter on the P-type semiconductor and the negative pole on the N-type. OK. Now let's reverse the probes of the ohmmeter: We are placing the positive probe against the N-type semiconductor and the negative probe against the P-type. Electrons flow off the metal probe and into the P-type semiconductor. No problem so far. On the other side of the diode the extra electrons from the N-type silicon are being attracted or "sucked" into the positive metal probe. Therefore the conduction seems to start out all right, but it isn't long before the extra electrons in the N-type silicon along the P-N junction are depleted. All that remains in this region are depleted valence 5 atoms that are now acting like pure silicon. This whole region now acts like pure silicon and the conduction stops.

So why can't the electrons that are migrating through the P-semiconductor holes hop across the P-N barrier and move onto the valence 5 atoms? The reason is the same. The migrating electrons have filled in all the holes in the P-type and the crystal has also become pseudo-pure silicon which is an insulator. At the same time, the extra electrons from the valence 5 contaminated semiconductor have all migrated out of the crystal matrix. Both halves of the diode have been converted into insulators. When thinking about PN diodes, remember, "positive to P conducts."

Real diodes

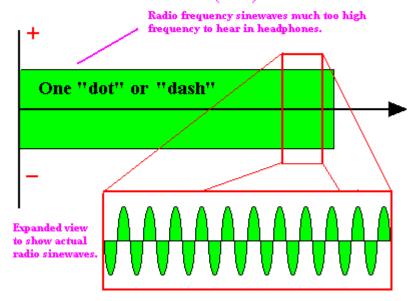
Commercial diodes come in all sizes. The types suitable for detectors in crystal sets are the little bitty guys on the lower left. The big black diodes on the right are rectifier diodes and diode "bridge" arrays for power supplies. The long black diode is rated at 6,000 volts. The two diodes that are built like machine bolts are high speed, high power units that might be used in a large switching power supply or an industrial RF generator.



Detection of AM radio signals with a diode

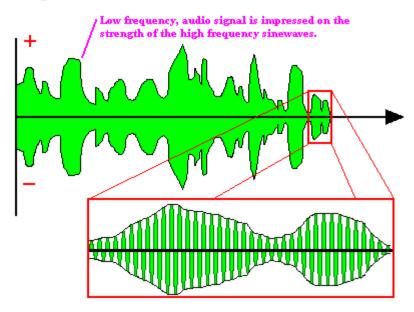
In amplitude modulation, (AM) the audio speech signal is impressed onto the radio signal by varying the AMPLITUDE of the radio signal. An AM transmitter literally increases and decreases the output power of the transmitter in time with the speech and music being broadcast. The drawing below shows an *unmodulated* radio signal of the sort used to send Morse code. The radio frequency sinewave remains the same amplitude throughout the time that the transmitter is keyed. Because the sinewave maintains its amplitude during the "dots" and "dashes," Morse code signals are known as *continuous wave* or "CW."

Unmodulated Radio Frequency Sinewave used to send Morse Code (CW).



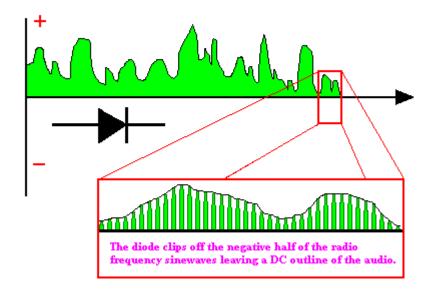
As the name implies, an *amplitude modulated (AM) radio broadcast*, (550 KHz to 1.750 MHz) makes a continuously varying graph of the RF signal that looks like a psychiatrist's Rorschach. But of course the outline of the audio signal is actually made up of hundreds of thousands or millions of RF sinewave cycles.

Amplitude Modulation of a Radio Wave



The diode detector recovers the audio signal by "shaving off" one of the two polarities of the RF signal. Sinewave currents have both positive and negative polarity. Diodes only allow conduction in one direction. So, when a radio frequency sinewave current is passed through a diode, one of those polarities will not pass and will be eliminated. What remains is a series of narrow, direct current pulses, all with the same polarity.

DIODE DETECTION OF AUDIO MODULATION ON A RADIO WAVE



This detection process, *rectification*, produces a varying DC signal that may be passed through a headphone to convert it into sound. If you try to pass radio frequency current through

a headphone or loud speaker, no current will flow and there will be no sound. The coil electromagnet in these devices is an inductor which has very high "impedance," AC resistance to current flow. By rectifying the radio frequency current, there is just low frequency audio frequency remaining. Many crystal sets put a small capacitor across the headphone to smooth out and remove the thousands of "bumps." In my crystal sets, there was no difference in loudness with or without the capacitor.

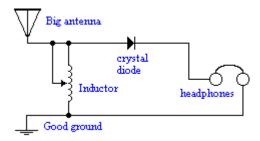
Physically, a modern detector diode is usually a tiny glass cylinder typically ¼ inch long with two wires extending from the ends. It's not much to look at. As will be described below, it's more fun to make a diode out of sulfide ore, or even out of razor blades or safety pins.

Headphones

After the diode has generated the varying DC current representing the audio signal, a device is needed to convert the current into sound. The classic way to do this is to use a magnetic headphone. As we shall describe below, a headphone is an electromagnet that attracts a thin, steel diaphragm and makes it vibrate in time with the speech and music.

A practical crystal set schematic

The crystal set can be extremely simple. A schematic is shown below:



Crystal Set Parts List:

Big antenna - 50 feet of wire strung up in a tree will be ideal. Or, use the 40 meter dipole described earlier. For this application, use the entire dipole assembly as if it were a single piece of wire. Connect the center conductor and the braided outer shield of the coaxial cable together and fasten the resulting "wire" to the "big antenna" location above.

Good ground – An ideal ground can be obtained by clamping the wire to a household copper water pipe. Alternately, you may use a second length of wire strung up in another tree. Ideally, the second wire should be far away from the first wire. I happen to have a 30 meter ham band dipole in my backyard. I used my 40 meter dipole in my front yard as the "antenna" and the 30 meter as a "ground." Or, as it would be called in this application, the 30 meter dipole became a "counterpoise."

Inductor - Wind about 20 turns of bare copper wire around a large diameter cardboard tube. Cardboard Quaker Oats boxes are the classic coil form for this purpose. The cardboard cylinder from a toilet paper roll will also work, but more turns are needed to produce the same inductance. I used to believe that large coils should work better because the coil is acting as a magnetic antenna, as well as a tuned LC circuit. In other words, a large diameter coil ought to be able to snag more magnetic field component from the radio wave. As you'll see later in the chapter, I was

unable to demonstrate the directionality of large coils at AM frequencies. Live and learn. To tune the crystal set, you need to rig up a slider or shorting clip that allows you to short out some of the coil.

Capacitor - Where's the variable capacitor? A capacitor consists of two pieces of metal separated by an insulator. If you wind a big coil of wire around a cardboard tube, then there is capacitance between one loop of wire and all the neighboring loops. "But, hold on! That can't be! They're shorted together!" you say. Yes, you're right. But if you look at an LC circuit as a whole, the inductor is a kind of "short circuit" across the whole capacitor and we know that works OK. The hard part about physics is that you often need to think abstractly. Many phenomena seem fuzzy and inconsistent. We are forced to "get a feel" for what works and what doesn't. The coil of wire is said to have *inter-winding capacitance* that acts the same as if it were a separate capacitor across the whole thing, honest.

Crystal diode - It's great fun to build your own diode as described below. However, to get started, you may want to use an ordinary, small silicon diode such as a type 1N4148 or a 1N914. They are available at Radio Shack and any other electronics semiconductor vendor.

Headphones. - You may construct a working headphone from ordinary materials as described below. This will be entertaining and educational, but eventually you will need to buy a good pair. You may buy either old-fashioned high impedance (2000 ohms) headphones or modern low impedance (8 ohms) headphones. The modern ones are extremely efficient, comfortable to wear and have hi-fi sound. They are also built from coils and magnets, their design is obviously much more sophisticated. The high impedance magnetic headphones are historic and little more can be said in their favor.

Homebuilt diode detectors

My experimentation with crystal sets as an adult began one day when I was hiking near Jamestown, Colorado. I was scrambling up a yellow-colored abandoned mine dump. Mine tailings up there are mostly yellow, sulfated, powdered rock that consists of broken-down granite or gneiss. Suddenly right in front of my face were chunks of the shiny, black sulfide ore that was the reason for the mine. Without an assay, I don't know exactly what's in this ore, but it's a safe bet that it's a mixture of sulfides of silver, lead, maybe zinc, a dash of arsenic, tin and copper. There might even be a trace of gold telluride in those crystals. Galena, lead sulfide, is the classic material used in old-time crystal sets to make detector diodes. I thought, "Gee! I wonder if I can make a crystal set out of this ore?"

It seems to me I once saw a war movie in which a POW in a Nazi Stalag made a radio out of barbed wire, a razor blade and silver paper from a chewing gum wrapper. Well, that's Hollywood, but maybe a receiver can be built without using parts specifically manufactured for radios. I happened to have a toy crystal set radio dating from about 1940 in my attic, so I hauled it down and checked it out. The "diode" consists of a tiny chunk of gray galena sticking out of a little puddle of solidified solder. The positive pole of the diode is a metal "cat whisker," a piece of thin copper wire poked against the crystal.

My crystal set project was done in three sessions and is written as separate articles.

Before you build the set pictured below, I suggest you read about the crystal set as described in the second article following this one. The second crystal set encountered some abstract mysteries, so although it worked better, it is harder to understand.



The above picture shows my crystal set with the three basic homemade components. The black "phone plug" connects the homemade earphone to the circuit. I used this standard connector so I could plug in a commercial headphone for comparison with the homemade headphone.

An LC resonant circuit is vital to select the AM radio band (or other band). An actual tuning capacitor isn't really needed at AM radio frequencies. A big coil, at very least two inches in diameter with 40 to 60 turns wound on a cardboard tube, has enough inter-winding capacitance to resonate in the AM band. From a physics point of view, the circuit in the "practical" schematic is functionally the same as the circuit that contains the variable capacitor across the coil.

Without a variable capacitor, you will have no way to tune in particular stations. A tap on the winding can be added for peaking a station. A "tap" is just a way to short out part of the inductor. Using this method you can crudely, very crudely, select the loudest stations at the top or bottom of the AM broadcast band. Tuning a crystal set is (usually) sloppy. However, the article at the end of this section demonstrates a way to accomplish sharp tuning.

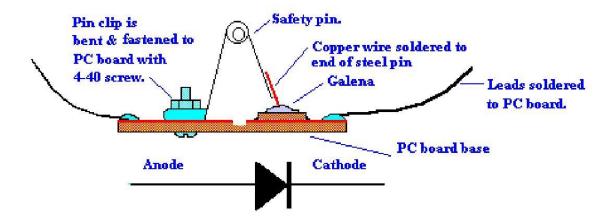
The crystal diode rectifies the radio frequency voltage ringing on the LC circuit and the headphones turn it into sound. Some crystal sets also have an audio signal filter or "integrator" capacitor. This capacitor, about 0.01 microfarad, is placed across the headphones. In theory, it converts the millions of little radio frequency halves into a smooth, low frequency audio waveform. However, in my crystal set it didn't do anything I could notice, so I took it out. Leaving out parts is a good way to find out what they do.

Try leaving out the LC circuit and just connect the diode and headphone to the antenna and ground. At my house all I could hear was faint static that sounded like power line noise.

That implies that power lines generate the biggest AM signals over the entire radio spectrum. In any case, without the LC circuit, I heard no radio stations.

The Jamestown crystal diode

To make my crystal detector out of sulfide ore, I melted a puddle of solder about 3/8 inch wide on a small piece of blank printed circuit board. Then I used tweezers to press a bit of ore into the puddle so that, when it hardened, half of the crystal was exposed. Next I soldered a thin semicircle of copper wire onto an isolated copper pad on the board for a "cat whisker." The copper wasn't springy enough to poke into the crystal with enough force for reliable performance. It worked well, but with a little vibration, it quickly died.



A safety pin pushes the copper whisker against the galena.

In my next diode I made a copper ring cut from the end of 3/8 inch copper tubing. This served as a deep "tub" of molten solder into which I could push the galena. Bob, NØRN, told me that when he was a kid, he used safety pins as cat's whiskers. Sure enough, the spring-loaded safety pin produced plenty of force and solved the mechanical problem. **Don't forget to cut the notch or gap in the circuit board between the galena side and safety pin side** – they are two separate nodes in the circuit!



Carbon steel is a semiconductor

When I first soldered my diode with the safety pin cat whisker into a crystal set, it was stone silent - nothing. No matter how I moved the sharp steel pin around on the galena, the headphones were dead. The pin happened to strike the solder at the edge of the galena and the crystal set came to life! I heard music from KBCU, our loudest local AM station. At first I was mystified. The steel pin rectified well against either solder or copper. The signal was perhaps only 2/3 as loud has it had been with the copper-to-galena diode, but it was much easier to adjust.

It turns out that steel is a carbon-iron semiconductor compound called cementite. The surface of hardened steel is a crystal, perhaps not radically different from the galena crystal. Carbon has a valence of four, just like silicon or germanium. Iron exhibits a valence of +2 or +3, but apparently that's close enough for this crude semiconductor. So, if you want to build a crystal set for your kids, *you don't have to mine galena. Just use a safety pin pressing against copper or solder.*

Another surprise for me was that copper-to-copper, solder-to-solder, or solder-to-copper junctions also rectify and produce weak signals. The contact between the two metal surfaces must be extremely light - just barely touching. This phenomenon is poor for making crystal sets, but it's a warning about bad contacts in electronic equipment. *Cold solder joints and loose screws could fill your circuit with accidental diodes.*

Copper cat whiskers work best

As shown in the diode construction diagram, I used *acid core solder* to attach a piece of copper wire onto the end of the pin. Rosin core solder sticks poorly to steel. Now the contact point of my diode is between semiconductor galena and copper, rather than semiconductor steel-to-semiconductor sulfide ore. I connected my crystal set to the center conductor of my 40-meter dipole coax and my station ground. I scratched the copper whisker around on the sulfide crystal and suddenly I was again hearing our local station. Using commercial 8-ohm headphones, it was almost painfully loud. Too bad KBCU is mostly rap music.

Where is the P-N junction in these crude diodes?

If you are a thoughtful person, you must be asking, "Where is the P-N junction with the impurities imbedded in the pure semiconductor and all that?" It turns out that you can make crude diodes by throwing together rather inferior materials. For example, pure galena crystal consists of lead and sulfur that have valences of 2 and 6, that sort of average to 4. But there are also all those other atoms in typical galena ore. These impurities, like silver or copper, have valences like plus 1, while other transition metals like tin have valences of 2 or 4. Let's just assume that because of sulfide (valence 6) and arsenic (valence 5) salts, my ore is a N-type semiconductor. So where is the P-type semiconductor? It turns out that if you press a pure metal against N-type semiconductor, metal ions will migrate a few microns into the N-type crystal. This makes a tiny P-type region surrounding the contact point of the "cat whisker."

As you might expect, the disadvantage of such crude diodes is that P-N junction is quite fragile. That is, the check valve function only works with very low voltages and extremely small currents. The P-N junction is easily destroyed if you put large reverse voltage across it or try to pass large currents through it.

I tried measuring the volt/ ampere characteristic of a steel/ copper diode. It was no surprise that it looked like a short circuit on an ohm-meter. I studied it carefully with a high

impedance multimeter and 10 megohm series resistors, but it still looked like a short circuit. I believe I just learned that *the world of RF detection is quite subtle*. At least the legend about POWs in WWII making radios out of barbed wire and razor blades is starting to make sense. The razor blade must have been the semiconductor.

Carborundum diodes

Carborundum, silicon-carbide, is an rock-like abrasive made by cooking silicon sand and carbon in an extremely hot oven. It's that black stuff on emery paper. Silicon is a semiconductor and a crystalline mixture of the two is also a semiconductor with unique properties. Ashish, N6ASD, gave me a sample to try out. It is a jet black, shiny crystalline material. The flat crystal facets have a blue-green and red reflective sheen, like oil on water.



The most primitive LEDs

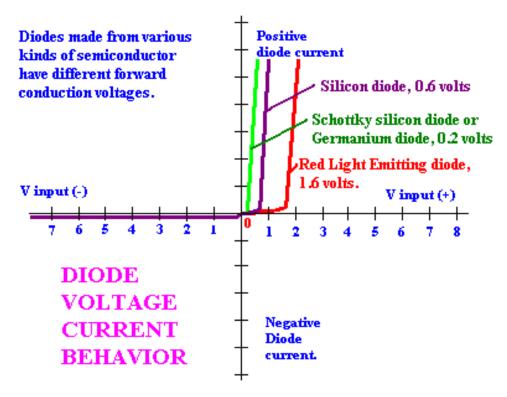
A curious property of silicon-carbide is that it can be used to make a crude, amber-colored LED. You apply a fairly high voltage to a piece of carborundum and, if you're lucky, the crystal around the contact point will glow weakly. Ashish demonstrated this using my 45 volt DC supply. After he left, I managed to make it glow amber too. Since then, I haven't been able to find any "magic spots" that glow. I did manage to heat up small crystals until they glowed red hot, like a glowing wooden match stick when the flame is first extinguished. However, the current was so high and the crystal so hot, it might as well have been a carbonized match stick. It was definitely not LED action. Perhaps this is why LEDs had to wait for the modern era.

In recent years, carborundum has been used to make high power Schottky diodes and blue LEDs. Although it sometimes occurs in nature, it is nearly always manufactured. I have read that the detector in the Titanic receiver used carborundum cat-whisker diodes. I made some diodes out of small pieces and yes, they worked well, but were much harder to adjust. The cat-whisker usually must be applied to the edge of a crystal rather than the shiny flat surfaces. Ashish told me that he read that biasing carborundum detectors with DC can produce a little more sensitivity. I did observe a slight improvement when I added a few milliamperes of DC bias. In summary, I prefer my crude sulfide ore diodes, but I'm no expert.

Commercial diodes

A perfect diode would have zero resistance in the forward direction and infinite resistance in the reverse direction. As you can see in the graph below, no real diode is perfect and all diode types have different forward voltage characteristics, depending on the semiconductors used to

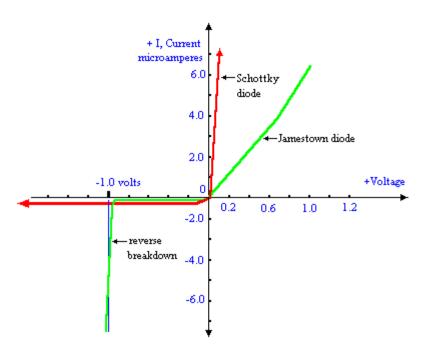
make them. The reverse characteristics of commercial diodes are all excellent and similar, but each type of semiconductor diode needs a certain level of forward voltage before it will begin to conduct. Commercial diodes handle hundreds of milliamperes or even hundreds of amperes. In the graph below relative current is plotted on the vertical axis. All three diodes were identical (purple) on the negative horizontal axis.



Commercial diode characteristics

Volt – ampere characteristics of homemade diodes

Once I had my cat whisker adjusted, the Jamestown diode was just as loud as a modern, hot-carrier Schottky diode. In theory, a Schottky should be comparable to a point-contact (galena crystal set) diode. Schottky diodes are commonly used as detectors in relatively modern equipment. If these diodes perform the same, how do their volt/ ampere characteristics compare? As you'll see below, homemade diodes can barely handle microamperes of current before they fail.



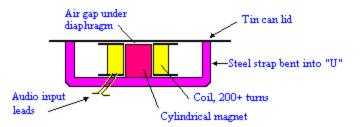
Volt / Ampere curves for the Jamestown diode and a commercial Schottky diode

At big voltages and currents, (milliamperes), the Schottky diode acted as you would expect: It passed big currents (milliamps) above 0.2 volts forward voltage and leaked only 100 nanoamperes with reverse voltage. Notice that if the Schottky were "perfect," the red line would be directly on top of the vertical axis upward, and directly on top of the horizontal axis to the left. However at very low currents, microamperes, the commercial Schottky was pretty nearly perfect with a transition right at zero volts.

In contrast, with big currents the Jamestown diode behaved like a resistor in both directions. At first it wasn't obvious to me that it could rectify anything. The curves above show the behavior of both diodes at tiny current levels, microamperes, using a 1 megohm (one million ohms) load. For tiny currents, the Schottky and Jamestown diodes were both strongly non-linear at the zero current, zero voltage point. The surprise for me was that, for reverse voltages, the Jamestown diode broke down abruptly at minus one volt. It's no wonder it conducted so well in both directions with a "low" resistance 10K ohm load. This abrupt, reverse breakdown is called *avalanche breakdown*. When it occurs with big currents, it usually produces so much heat that it destroys the diode. As we'll see in Chapter 8, some diodes called *Zener diodes* are designed to breakdown at specific voltages without being destroyed.

A homemade headphone

Building my own headphone was the most difficult part of my crystal set. A headphone uses a high impedance coil of wire to make a magnetic field proportional to the audio signal. The changing field pushes and pulls against a thin steel diaphragm to produce sound vibrations. Even if you decide to build one of these headphones, I strongly suggest you buy a good pair of headphones so you will have them for your ham rig. Also, with commercial headphones the speech and music will be perfectly clear and loud in the crystal set.



The Caribou headphone

A cross section of my homemade headphone is diagramed above. Its construction is basically the same as old-fashioned high impedance headphones. Yes, the sound is tinny. What did you expect from a headphone diaphragm made from a tin can lid? The coil is hundreds of turns of #36 wire wound on a paper coil form. Inside the coil is a cylindrical magnet I took out of an old loudspeaker. A piece of steel strap conducts the magnetic flux around to the edges of the lid. The magnetic force holds the lid on. By completing the magnetic circuit loop, the magnetic force is concentrated in the gap between the tin-plated steel and the magnet.



Crystal set showing homemade headphone. The tin can lid diaphragm has been removed.

I started out using a small magnet from an old loudspeaker, but that felt like cheating. Would Heinrich Hertz have been able to use a loudspeaker magnet? Anyway, it seemed to me that the magnet wasn't essential. Why couldn't the coil just magnetize ordinary iron? I tried substituting a big steel nut of the same size. Sure enough, it worked, but the sound was too faint to be intelligible in the crystal set. However, when I plugged the homemade headphone with the steel nut into my shortwave radio, it was surprisingly loud. Not Hi-fi, mind you, but loud. Clearly a sensitive headphone needs a magnet to overcome the hysteresis.

Hysteresis

What's "hysteresis," you ask? A mechanical analogy is the meshing of two loose gears,

perhaps in an automobile transmission. If the gear teeth are not in close contact, then when one gear begins to turn, there will be a slight delay before the teeth engage the second gear. When the direction of the first gear reverses, there is another delay while the teeth travel across the gap and engage the second set of teeth. On the other hand, if the first gear never reverses direction, the teeth remain engaged and there are no delays.

Iron core inductors also have this delay problem. Whenever iron is magnetized with a DC coil, the tiny "magnetic domains" in the iron line up to make a big magnetic field. But when the DC current is shut off, some of the magnetic domains remain aligned and leave a residual field. To magnetize the iron in the opposite direction, a current of the opposite polarity must first overcome the residual field. This means that hysteresis interferes with the sensitivity to weak signals. Since crystal sets are powered by the radio waves themselves, sensitivity is vital. A magnet is needed to overcome the hysteresis and "bias" the magnetic field so that it always operates in one direction. I could magnetize iron with a DC powered coil, but then to be a purist, I would need to build a homemade battery. And I would need to smelt and extrude my own copper wires. Unfortunately, or perhaps fortunately, there are limits to what we can do in our basements.

I had a sudden inspiration. I dug around in my rock collection and found a piece of magnetite ore from a mine dump at Caribou, Colorado. Magnetite is a specific iron oxide, Fe₃O₄,, that retains a magnetic field. It is grey-black in color and surprisingly heavy. I machined the magnetite with my bench grinder into a small cylindrical magnet. Unfortunately, the grinding and heat ruined the magnetism. However, fixing it to a big, heavy permanent magnet, I was able to put my magnetite in a strong magnetic field. Then I banged on it firmly against my anvil. Believe it or not, that abuse restored the magnetic field. Behold! - The completed Boulder County rock and toilet roll radio!

How does it perform? Well, frankly the homemade headphone is pathetic and needs lots of R & D. The sound is plenty loud when plugged into a real radio, but installed in the crystal set, I can just barely hear the rap music. Perhaps if I had a thinner steel diaphragm, a headphone for each ear, optimum impedance matching, better craftsmanship and other refinements, it might approach a commercial headphone. In other words, for serious listening, buy a decent headphone! And, after you're done playing with homemade crystal diodes, I suggest you buy some silicon diodes. Ordinary type 1N914 or 1N4148 diodes work great in this radio. *They do NOT work better than the diode made from sulfide ore*, but they are smaller, more rugged and don't need to be carefully adjusted.

This crystal set article was first written in 2002. I revisited crystal sets in 2006 and 2017 and discovered some surprises.

CRYSTAL SETS REVISITED

Or, electronics makes us humble

A friend of mine, Jack Ciaccia, WMØG, suggested to his grandson, Rutger Koch, that a broadcast band crystal set like the one described above would be a good science project. Rutger did a terrific job of duplicating the set and the homemade diode. The only obvious difference I

could see was that he had used the 5-inch cardboard oatmeal box coil form that I had recommended. But when Rutger put it together, it was totally inert - no sound.

Rutger consulted his granddad who also couldn't find anything wrong. Jack brought the crystal set over to my house and we two old hams scratched our heads and still couldn't find the problem. After five minutes of swapping parts, I dug out my prototype crystal set from the closet and there was the answer: If you go back to the drawing of the homemade diode made out of the piece of PC board and a safety pin, you will see that there is a notch carved in the PC board between the anode and cathode. Rutger had forgotten to cut the copper sheet between the anode and cathode so they were shorted together. We cut the copper sheet and it worked perfectly. *Our eyes only see what they expect to see!* Don't take the obvious stuff for granted. By the way, Rutger's science teacher refused to believe rocks could serve as diodes until he put on the headphones. This ancient technology is all new information for whippersnappers.

Does a bigger diameter coil work better?

When I first built my AM broadcast band crystal set described earlier, a toilet paper roll was the largest diameter cardboard form I could find around the house. Although I hadn't noticed any obvious superiority in Rutger's crystal set over mine, I decided to wind a big coil like his and see if my magnetic antenna theory had any validity. That is, the big coil might pick up the magnetic wave components and produce a bigger signal. Perhaps it would be directional like an AM band ferrite core antenna, the kind of antenna in your little battery powered radio. Since my crystal set had previously been converted to 10 meters (see the next article, below), I just took off the loop antenna and left the 140 pF variable capacitor on the set. Then I installed the oatmeal box coil with about 25 turns on it. Since I already knew that ordinary silicon diodes have the same sensitivity as the rock diodes, I used a 1N4148 diode and my large, low impedance headphone.



Oatmeal box crystal set - operating without a ground or counterpoise

I hooked up the 40-meter dipole antenna, "A" above, and used the 30-meter dipole as a counterpoise connected to the ground post, "G" above, just as I had before. This was the same way Jack and I had hooked up his grandson's set. The silence was deafening. Good grief! Now what?

After some flailing about, I accidentally disconnected the counterpoise wire as shown above, just leaving the antenna wire connected. Voila! It not only worked well, the tuning was precise enough to tune in my local NPR station at 1490 KHz with excellent selectivity and signal strength. Specifically, when tuned to 1490, there was no rap music from 1190 KHz! Tuning was not only loud and clear, I could only hear the one station and not 2 or 3 at once. Precise tuning with a crystal set! How is this possible? When I padded the relatively small 140 pF variable capacitor with 100 pF fixed capacitors, I was able to tune down the AM broadcast band and uniquely select other stations. The farther down the band I went, the less precise the tuning. I have no good explanation for that. If I were starting over, I would use a larger variable capacitor, e.g., 365 pF.

How does this work?

The selectively tuned crystal set seems to be an example of a circuit that doesn't seem to have a complete circuit loop. Without a ground or a counterpoise, where does the current go? I assume that there is some form of capacitive coupling that completes the loop, but I admit this coupling isn't obvious. As you can see, RF sometimes makes current loops that are hard to identify.

Using the backyard antenna as a counterpoise didn't work with the big coil, but I found that clipping the ground terminal, "G" to my station ground did improve signal strength. Unfortunately, it ruined the precision of the tuning. Hooking it to the station ground and the counterpoise antenna together still worked, but was weaker and produced poor tuning. Using the backyard 30-meter dipole as the sole antenna, worked just as well as the 40-meter antenna.

I probed with my oscilloscope at various places on the circuit to get some answers. As soon as I clipped on the oscilloscope probe ground wire, it behaved just like the grounded hook up, just as you would expect. The signal strengths across the coil were on the order of 0.40 volts peak. The power delivered to the 8-ohm headphones was about 20 milliwatts peak. The most surprising observation was that, when I just left the scope probe and its ground wire lying six inches away from the crystal set, I could see the modulation on the oscilloscope screen appear and disappear as I selected specific stations. The voltage signal was only slightly less than when it was directly connected. Apparently *there is a large electric RF field surrounding the crystal set*.

When the RF current passes through the LC circuit and headphone to ground, the current passing through the diode and headphone is relatively large. This makes lots of sound, but all the local station signals present pass through at once. When the RF current has nowhere obvious to go, the RF voltage can only leave by weak capacitive coupling to the surroundings. With no ground the only source of current for the headphone is the oscillating RF voltage ringing on the LC circuit. This small RF voltage provides the highest voltage only when the LC circuit is precisely tuned to a station. Otherwise, you only hear silence.

"Q" is the quality of a capacitor or inductor

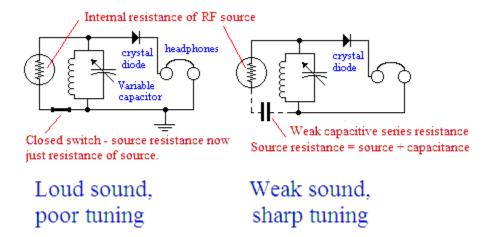
The "Q" or "Quality factor" is defined as the reactance, i.e., AC resistance, "X," of an inductor or capacitor divided by the DC resistance of the reactance. $Q = X \div R$ Capacitors nearly always have a very high Q. This is because the DC resistance of the capacitor leads and energy losses in the dielectric insulator are usually insignificant. In contrast, the Q of a coil inductor can be low, because the DC resistance of several feet of fine copper wire can be quite significant. Also, if there is an iron core, there are more losses in the magnet. Low Q components in an LC circuit makes the tuning less selective. The resistance in an LC circuit dissipates and attenuates the current circulating back and forth between the inductor and the capacitor. The practical effect of this is that the tuning is less sharp.

Similarly, when a low resistance is put *ACROSS* an LC circuit, this resistance steals energy from the oscillating LC circuit. This rapidly extinguishes the RF voltage across the LC circuit and has the same effect as resistance *INSIDE* either the L or the C. When the oscillation is suppressed, the effect of the resonance becomes "mushy," the resonant frequency widens and the peak voltage across the LC circuit is reduced. When our crystal set is grounded, this apparently puts a much greater load on the LC circuit. The greater current load extracts more energy from the LC circuit, which we observe as much louder volume from the headphones. As you will discover, the price of loud audio is poor tuning.

Radio signals considered as an RF voltage generator

Another way to look at this problem is that we can consider the radio signals as an AC voltage generator referenced to ground. Like other circuits there must be a circuit loop for any current to flow. It turns out that power (energy per second) is most efficiently transferred from source to load when the resistance of the load equals the internal resistance of the source.

Little 9 Volt transistor batteries have very high source resistance. Big energy sources, like the alternators at the Boulder Dam in Nevada, have extremely low internal resistance. Our RF source - an antenna and ground - also has an internal resistance. When the connection between the crystal set and ground is a short circuit, the internal source resistance is just the internal resistance of the radio wave with respect to ground. But when the crystal set is floating, the total internal source resistance becomes the radio wave source resistance *plus* the weak capacitive reactance.



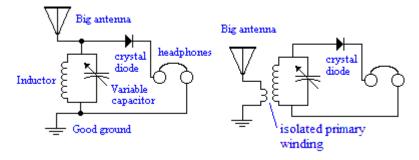
As explained earlier, LOW EXTERNAL resistance across the LC circuit is equivalent to

HIGH INTERNAL resistance. This lowers the Q and produces lousy tuning. Alternately, HIGH EXTERNAL resistance is equivalent to LOW INTERNAL resistance in the LC circuit and makes the Q high and produces sharp tuning. In the illustration above, the "weak capacitance" can be made variable using an actual variable capacitor.

Maybe you have your own ways to explain these phenomena. Feel free to pontificate. Obviously we old hams don't know everything, even the simple stuff! Keep your brain engaged and question authority.

Fast forward to 2017

Ashish Derhgawen, N6ASD, produced *more audio volume from his crystal set by using an RF transformer design*, rather than a simple inductor. The antenna goes to a small primary winding with relatively few turns. The opposite end of the primary goes to ground. The secondary is the larger winding which resonates with the tuning capacitor. This design "steps up" the voltage across the main inductor, while decreasing the current through it. Ashish's diode and headphone go across the entire secondary winding. I put a similar 5 turn isolated primary winding on my crystal set and observed the same improvement. Unfortunately, the selectivity of the tuning did not improve when wired as shown below.



Ashish also invented a simple homemade variable capacitor. It consists of an aluminum soda can wrapped with a paper insulator and aluminum foil. When the sleeve slides up and down on the can, it can tune over a 400 pF range. The paper insulator can be labeled with frequencies and stations. Brilliant!

Autotransformer antenna connection

Inspired by Ashish's experiments, I achieved a similar improvement using a tapped main coil rather than a separate winding. The coil on my oatmeal box crystal set has 25 turns. I sampled several spots on the coil and found the best tap for the antenna was at 5 turns up from ground. This results in an "autotransformer." That means the voltage to current ratio change is done within the same winding, rather than using separate, inductively linked windings. An autotransformer has the advantage that the connection between the "primary part" and the "secondary part" of the transformer are as tight as possible. Linkage efficiency isn't an issue because they are one and the same winding. The disadvantage of autotransformers is that they lose the isolation feature of a floating secondary winding. If the primary of an autotransformer is grounded, so is the secondary. When not connected to ground, this set tunes sharply and receives two local stations well. The stronger of the two is uncomfortably loud. The other stations are too faint to hear.

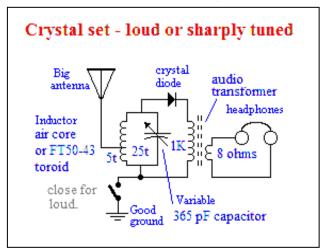
I wondered if a similar coil wound on a tiny FT50-43 ferrite toroid would work as well as the big oatmeal box coil. 25 turns on the toroid performs exactly the same. I scratched off the enamel so I could sample every turn as a location for a tap. As before, maximum volume occurred with antenna connected to a tap at 5 turns, 20% of the coil. My big earphones are low impedance (8 ohm) and the LC tuning coil tunes sharply when operated with no ground.

Matching the headphones to the high impedance LC circuit

It occurred to me that the headphone, especially an 8 ohm one, is low impedance and would be better matched to a low impedance tap on main coil. To find out I rebuilt my crystal set with a low impedance taps for both the antenna and the headphone. The output was slightly louder with diode connected to a tap.

Next I tried using an audio loudspeaker transformer across the LC circuit instead of attaching the headphones to a tap on the LC coil. The transformer is designed to convert a high impedance source, 1,000 ohms, to a low impedance load, 8 ohms. In case you're wondering, a high inductance winding on an audio transformer will look like a very high impedance at radio frequencies. In other words, it looks like an "RF choke." I reasoned that the transformer should produce more audio volume than putting the diode and earphones directly across the high impedance LC circuit and might work better than the tap. It's *much* better! With the ground connected, in a quiet room I can hear the headphones clearly with them lying on the table, 3 feet away. As before, to hear the other local station, I have to un-ground the set and wear the headphones. I padded the variable capacitor with a 180 pF fixed capacitor to be sure that the variable capacitor could tune down at least as far as the bottom of the AM band, 550 KHz.





When the ground is open circuit, the connection is simply stray capacitance between the circuitry and ground. This weak capacitance gives good tuning, but very weak volume in the headphones. That is, only one station was actually really loud enough to enjoy. By replacing the "sharp vs. loud" switch above with a 140 pF variable capacitor I was able to adjust the compromise between "loud" and "sharp tuning." The capacitor resembles a variable resistor and serves as an "RF sensitivity control." With the correct extra capacitance, I was able to receive 3 stations loudly enough to hear voices and music clearly. Without the variable capacitor, only one station was loud enough to enjoy, and that one station obliterated the other two.

As I experimented, I realized there are hundreds of different ways to build a crystal set.

There will always be a different, slightly better way to tap here, couple there, add another diode, and add multiple LC circuits. If you check out www.makearadio.com, Dave, N2DS, has built 78 crystal sets and is happy to tell you about all of them! Obviously this quest can be addictive and endless!

While I was experimenting with crystal sets, I dug out an ancient crystal set module from my junk in the attic. I have no recollection of who gave this to me, but it is easily over 100 years old. The components are the highest quality - brass variable capacitor, Bakelite end plates, a fancy aluminum cover for the coil and the galena crystal which is imbedded in a little solder-filled socket. This was part of a serious adult radio, not a child's toy. The original set must have had other LC circuits or components that gave it sharp tuning. Otherwise the cost of the fancy capacitor would have been wasted.



I wired the old components just like my set, shown previously. Voila! It worked the same - not better and not worse. It would be interesting to examine the original complete crystal set to see how commercial "adult" radios were designed prior to vacuum tubes. I'll bet some of the earliest vacuum tube radios used a tube to amplify the audio signal. That would make the fine tuning mode completely practical - perhaps even driving a loudspeaker.
