Crystal Radio Engineering
Diode Detectors

by Kenneth A. Kuhn
Feb. 3, 2008, (draft – more to come)

A diode is a non-linear device that conducts electrical current significantly better in what is referred to as the forward direction than in the reverse direction. This process can convert an AC signal to a DC signal through a process known as rectification. If the amplitude of a high-frequency AC signal is varying in response to a low-frequency amplitude modulation (such as audio) then rectification will result in a varying DC signal with the modulation superimposed. The original audio signal is recovered by discarding the DC term.

Although the term, threshold, is often used in discussions about diodes in regards to some minimum signal no actual threshold exists. The forward resistance of the diode generally has a reciprocal relation to the forward current – i.e. the diode conducts better as the forward current increases. The poor conductivity of diodes at very low currents gives rise to the “threshold” discussion. A diode ideally has no conductivity in the reverse direction although all diodes will exhibit some reverse conductivity and a number of excellent microwave diodes have significant reverse conductivity as a consequence of their internal structure. Reverse conductivity works against us but what is more generally important is the ratio of forward to reverse conductivity – the higher the better.

Diodes in the early days of radio were homemade and typically consisted of the junction of some metal such as a stiff wire against a non-metallic conductor. Considerable effort was required to locate a “sweet spot” that had good diode qualities. Some purists still insist on this method today and that is fine but I highly recommend that you purchase a manufactured diode (such as a 1N277) made for the intended purpose. You will be much happier and satisfied with the performance. After you have a working crystal radio you can experiment with ancient methods – always begin with a working circuit before trying something different or challenging.

Commercial diodes that can be used for crystal radios include the germanium diodes 1N34 and 1N277 (note: the 1N277 has in most cases replaced the old 1N34), silicon diodes such as the 1N914 and 1N4148, and a variety of microwave diodes with the Avago (formerly Agilent and formerly HP) 5082-2835 being a popular choice. Until the advent of microwave diodes the germanium diodes were and still are very popular because they work so well for crystal radios. Microwave diodes were never intended for use in crystal radios but they have significantly better conduction that silicon although they are not as good as germanium. However, germanium diodes are sometimes hard to find and microwave diodes are relatively easy to find. Some microwave diodes have a noticeable reverse conductivity which detracts from their performance but overall many microwave diodes can do an excellent job. I would definitely try several of them. Silicon diodes are a poor choice for crystal radios because they have very low conductivity at very low currents – i.e. they are very lossy. But, if you are in a strong signal area and do not have better diodes, then silicon is much better than nothing and you can make a working crystal radio. But, you will want to upgrade to a diode better for the purpose as soon as you can. If you are driving very high impedance headphones such as the crystal type then you may find that silicon is not too bad. Figure 1 shows the current versus voltage curves for several common diodes. These plots were made using an XY recorder.

Note that the germanium diode shows significantly better forward conductance than the other diodes. On the scale shown it is possible to see the reverse resistance of that diode which is about 100 k. The reverse current for the other diodes does not show up on the scale. Note that the forward current of the silicon diode barely shows up on the scale.

The silicon 1N4148 diode barely shows any forward conductivity at these low forward voltages. This graph clearly shows why silicon diodes do not work well in crystal radios. The transfer curve of a popular microwave diode is also shown. The diode has significantly better forward conduction than silicon but is not as good as germanium.

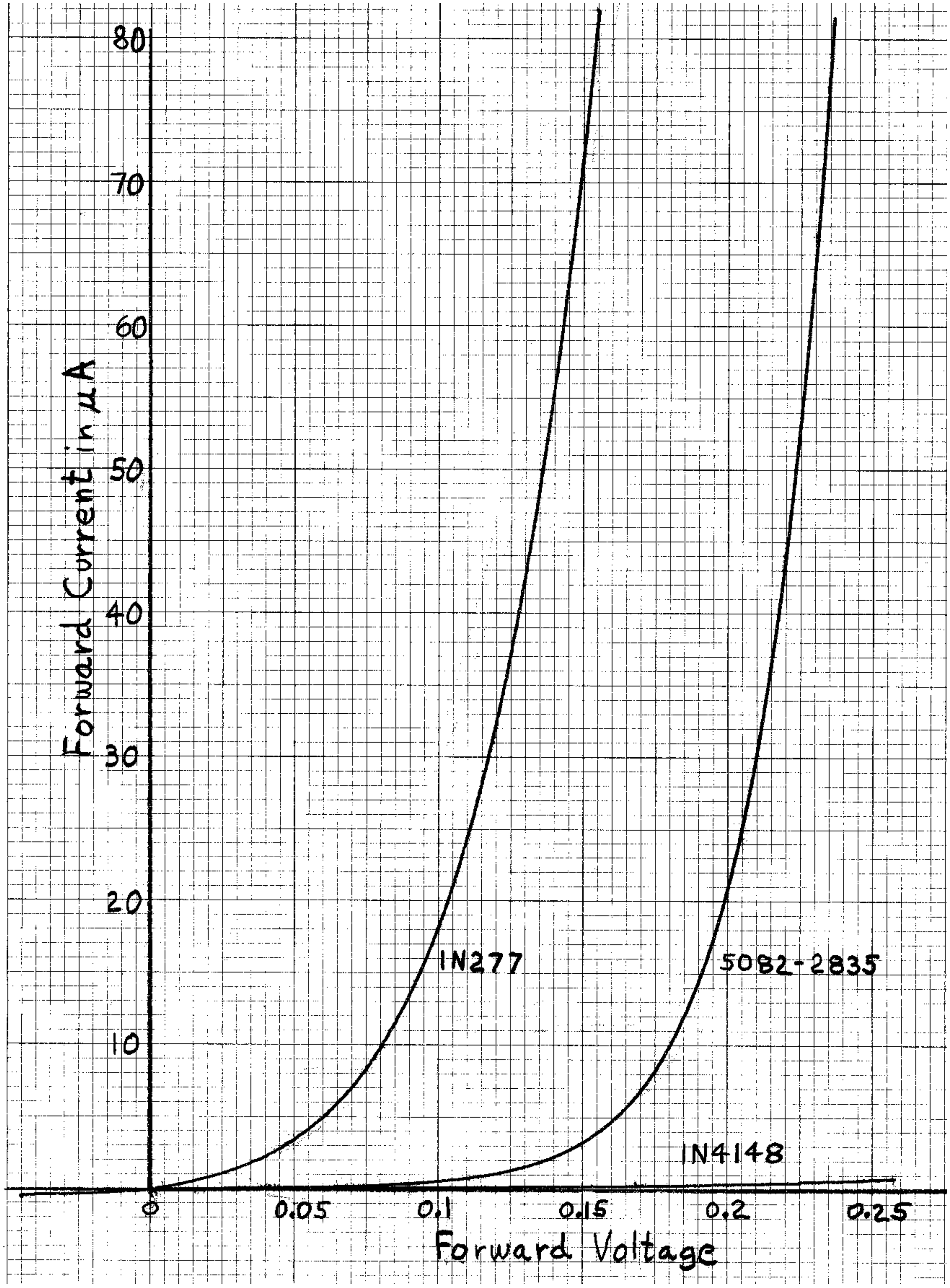


Figure 1: Diode Curves

Crystal Radio Engineering
Diode Detectors

There are two fundamental types of rectifier circuits, series and shunt. Series is probably the most common but shunt can work well too. I recommend that you try both. Whether series or shunt, the most common circuit is half-wave using only a single diode. Neither of these two types of rectifier circuits is superior to the other. But there are various esoteric viewpoints that drive different people to one or the other configurations. My advice is to use the one you like.

It is desirable to perform the rectification process at the highest voltage possible in the radio. This voltage is the entire voltage across the resonant circuit. One problem with this is that the headphone impedance may be low which will result in the tuned circuit being overloaded – thus low signal and poor selectivity. There are two solutions. One is to connect the diode to an appropriate lower impedance tap on the inductor. The other is to use a transformer to magnify the headphone impedance. Each method can work but the second method is the better option if the right transformer is available. Otherwise the first option is better. Small signal audio transformers tend to be very lossy. It is not uncommon to lose 30 to 50 percent of the audio power. If you use a transformer, consider a larger one physically so that losses will be in the 10 percent range.

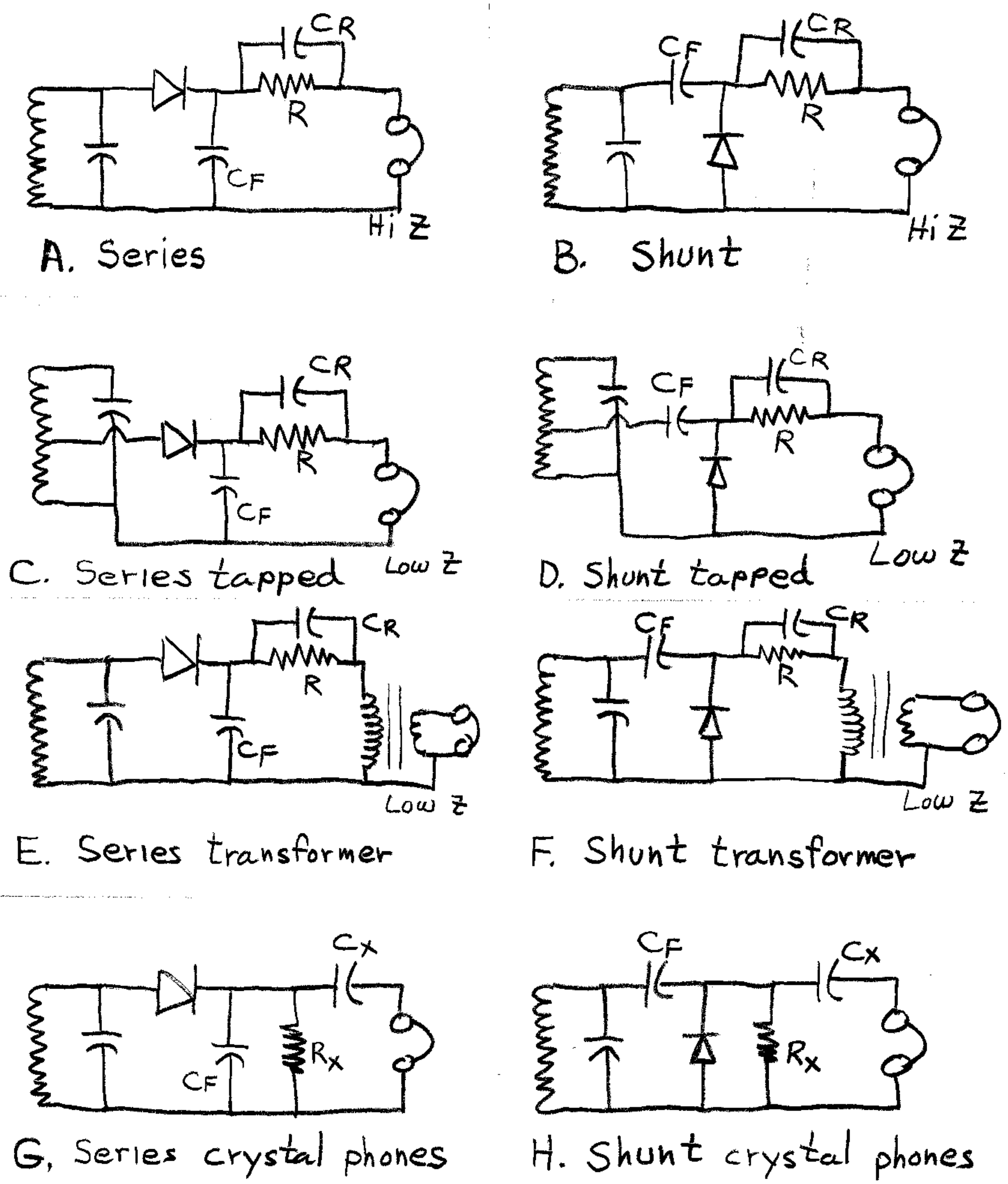
Figure 2 shows various diode detectors. Many of the circuits show a series resistor, R, with a shunt capacitor labeled CR. The purpose of this network is to make the AC and DC loads as similar as practical. Differences in these loads cause distortion and even weak detection in some cases. This network is often omitted and the results may be satisfactory but the best results will be obtained with the network. See Reference 1 for a detailed discussion. The resistor, R, is roughly equal to the midband impedance of the magnetic headphones or transformer primary minus the DC resistance of the coil. The purpose of capacitor, CR, is to form an AC bypass around R so that there is no signal attenuation. CR is of such value to form a time constant of about 1 to 3 milliseconds with R.

The purpose of capacitor, CF, is to filter the RF signal without affecting the audio. CF is of such value to form a time constant of about 10 to 30 microseconds with the load impedance – either the magnetic headphones or the transformer primary.

When low-impedance headphones are used then the resonator coil must be tapped appropriately so that there is a proper match of impedance.

When crystal headphones are used there needs to be some large resistance, RX, (typically in the fifty to several hundred thousand ohms) across the detector output for a DC load and a coupling capacitor, CX, to block any DC voltage from being across the crystal headphones. The value of CX should be large enough to pass low audio frequencies. The value needed will depend on the headphone characteristics but values in the 10 to 100 nF range are typical.

Crystal Radio Engineering
Diode Detectors



A. Series
B. Shunt
C. Series tapped
D. Shunt tapped
E. Series transformer
F. Shunt transformer
G, Series crystal phones
H. Shunt crystal phones

Figure 2: Various diode detectors

The detector places a load resistance on the resonant circuit it is connected to. For very large signals the load resistance is roughly twice the impedance of the headphones as conduction only occurs for one half cycle. The load impedance for very small signals is higher because of diode losses.

There are myths that full-wave rectification is superior to half-wave and delivers twice the audio signal. In practice that is hard to achieve because diode losses become more significant. Full-wave rectification roughly halves the load impedance seen by the resonant circuit. That in turn lowers the operating Q by roughly half which means that roughly half the voltage is developed. The process just described tends to negate any apparent advantage of full-wave rectification. The scenario for full-wave detectors to work their best is for the load impedance to be very high such that the net load on the resonant circuit is optimum for maximum power transfer. However, the losses using two diodes will always be higher than for one. My advice is to stick with half-wave and try a variety of diodes in a search for one that delivers the most audio signal.

***** Note: the following is very rough – more to come soon – a lot of material is missing at the moment *****

A simple capacitor filter is used on the

It is important that the DC load on the diode be as nearly identical to the AC load as possible. Any difference in loading can cause signal loss and distortion.

Show diode plots. show conductance plots. show efficiency calculations. Use actual diodes.

We can model the diode detector as an ideal diode (i.e. zero series resistance and no voltage drop when forward biased) in series with a resistance as shown in Figure _. The diode does not have a “threshold” voltage – it is just that at low signal amplitudes the effective series resistance is very high which causes a high voltage division factor.

The following figures illustrate several common diode detectors.

Plot of input impedance to diode as function of signal amplitude and load resistance.

The typical signal applied to the diode in a crystal radio ranges from less than one millivolt for a very weak signal to perhaps several hundred millivolts for a very strong signal. In special cases with a nearby (less than about 10 km) station the signal might be over one volt. Our primary interest is the diode response to small signals in the ten to one hundred millivolt range.

A test circuit was constructed as shown in Figure 3 to measure the characteristics of a 1N277 diode at very low signal voltages. The RF signal generator makes a 1 MHz signal with 50 percent amplitude modulation of a 1 kHz sine wave. The RF signal generator has a 50 ohm output impedance and a terminated 50 ohm attenuator was used to make the small signals. This results in a 25 ohm source impedance to the diode which is negligibly small. Load resistances of 2K, 5K, 10K, 20K, and 50K were used and the filter capacitor was 10, 3.9, 2.2, 1.0, and 0.47 nF respectively to provide a low-impedance path for RF without excessive filtering of the demodulated audio. The nominal time constant of the filter is 20 microseconds which results in an audio cutoff frequency of 8 kHz. The 100K resistors in series with the DC voltmeter and AC voltmeter served the purpose of reducing any signal pickup from the connecting cables in an effort to reduce errors.

Figure 3: Test setup

For each load resistance, the attenuator was switched in 2 dB steps from 0 down to -36 dB and the DC voltage and AC signal voltage was measured. This data was used to make the following plots.

Figure 4 shows the detected DC voltage versus the applied signal for the load resistances shown. The transfer curve of a theoretical ideal diode is shown for reference. Note that the higher load resistances result in a higher detected voltage. This is especially true at very low applied voltages. Figure 5 is the same data plotted using logarithmic scales which expands the view at very low signal voltages.

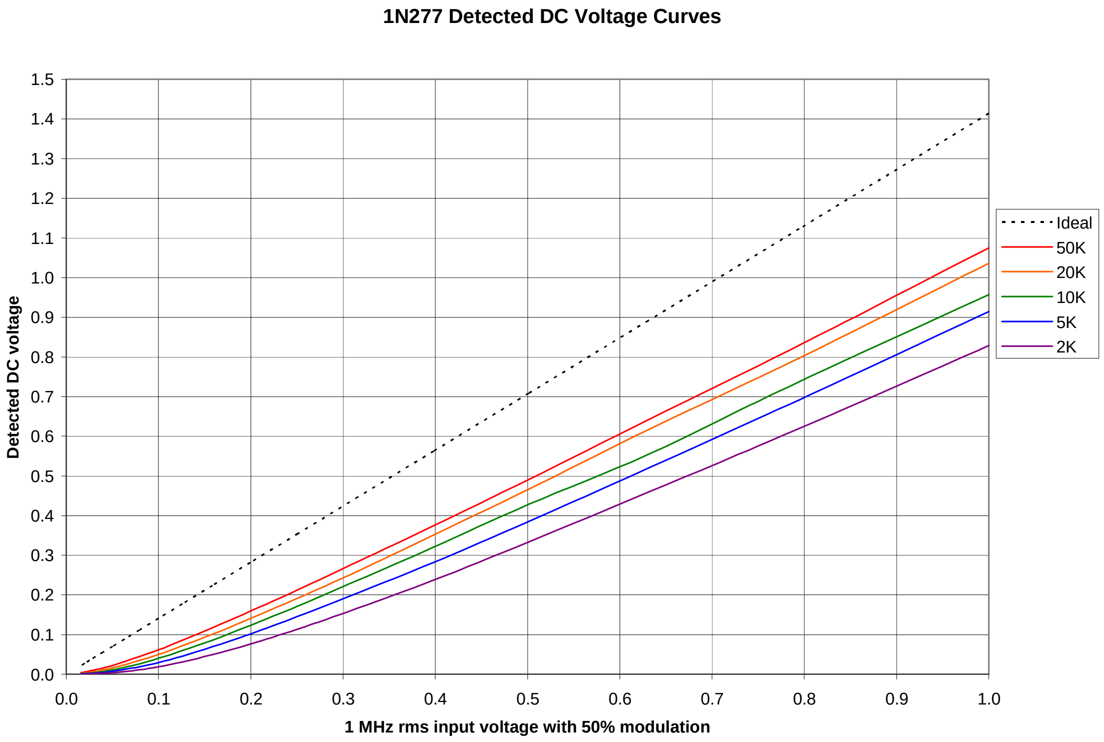


Figure 4: Family of curves showing detected DC voltage

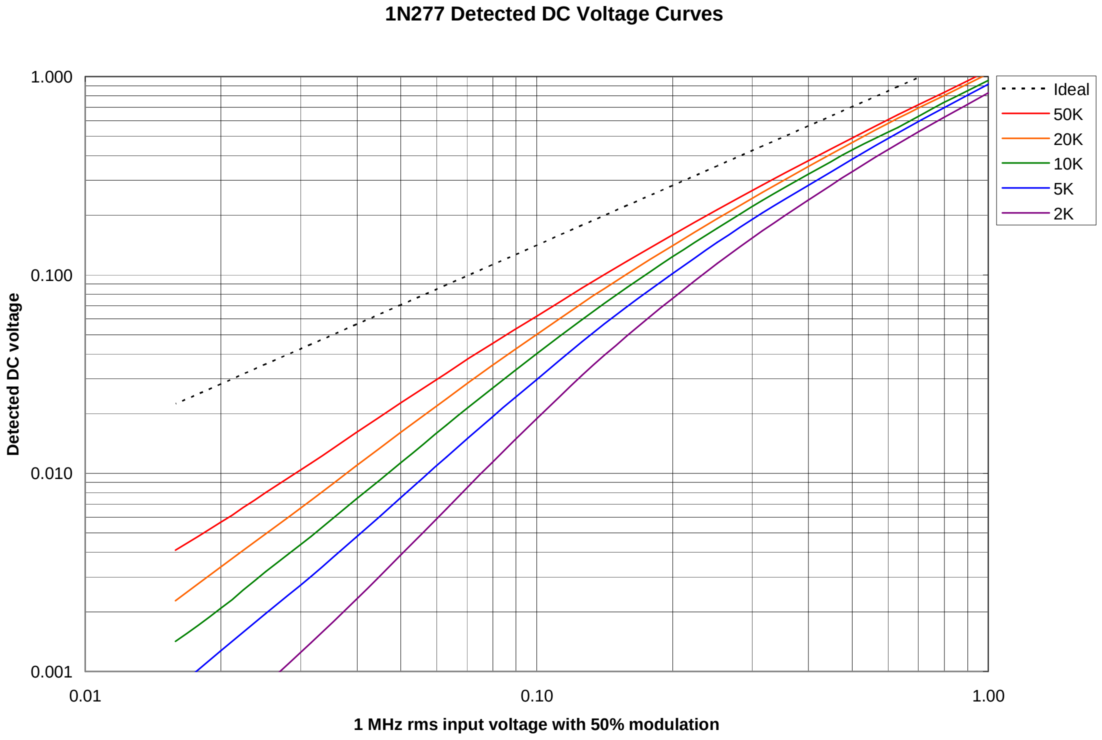


Figure 5: Family of curves showing detected DC voltage

Figure 6 shows a family of curves of the demodulated signal versus the applied voltage for the resistance loads given. The detection of a theoretically ideal diode is shown for reference. Figure 7 shows the same data plotted on logarithmic scales.

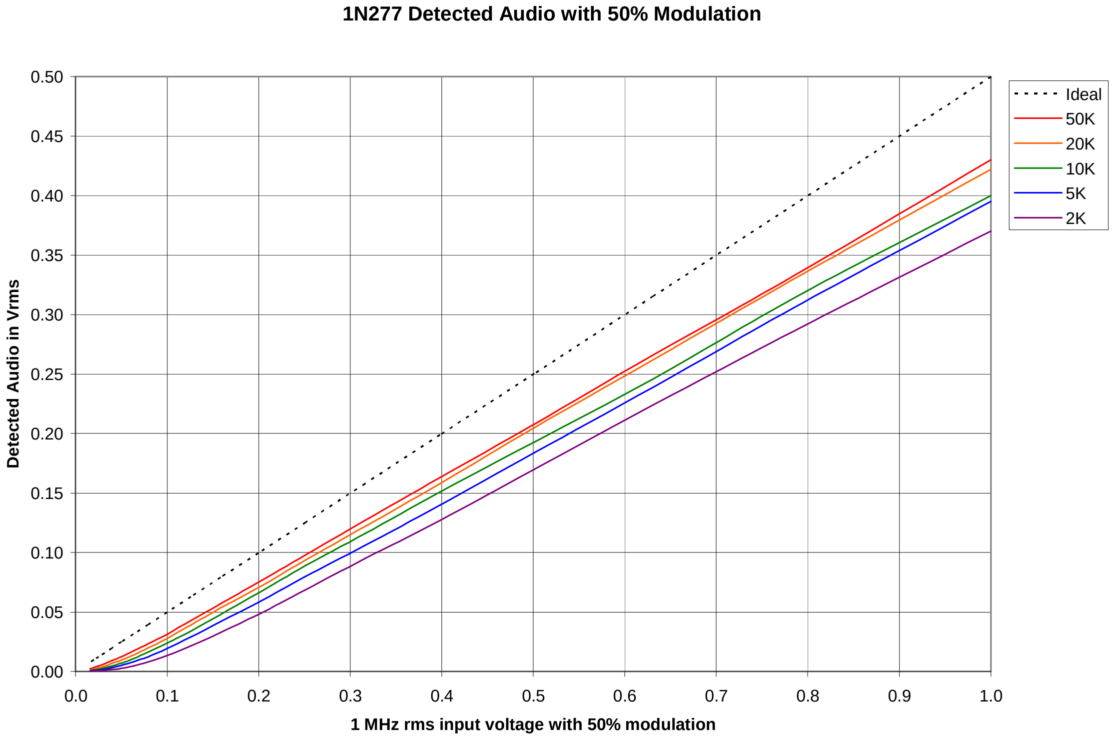


Figure 6: Demodulated audio signal amplitude versus applied voltage

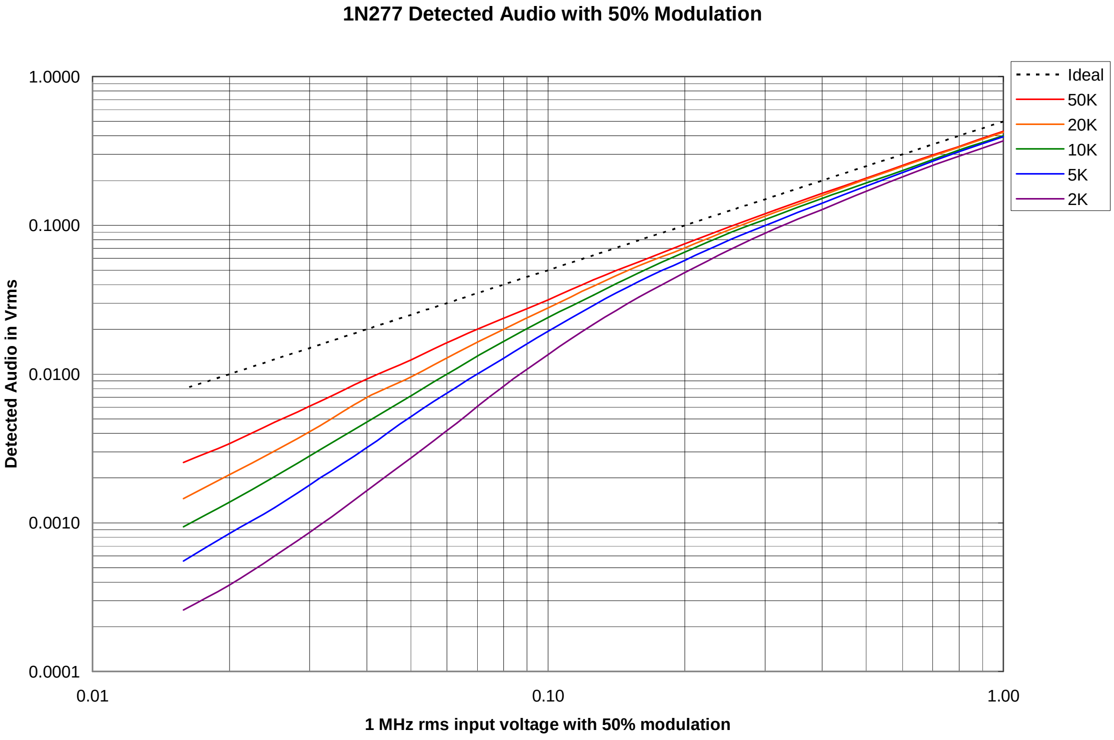


Figure 7: Demodulated audio signal amplitude versus applied voltage

Crystal Radio Engineering
Diode Detectors

The diode can be modeled as ideal (i.e. zero voltage drop and resistance) in series with a resistance that is a function of the applied signal. The net demodulated signal is the result of voltage division between this resistance and the load resistance. This series resistance becomes high at low signal levels resulting in poor rectification efficiency.

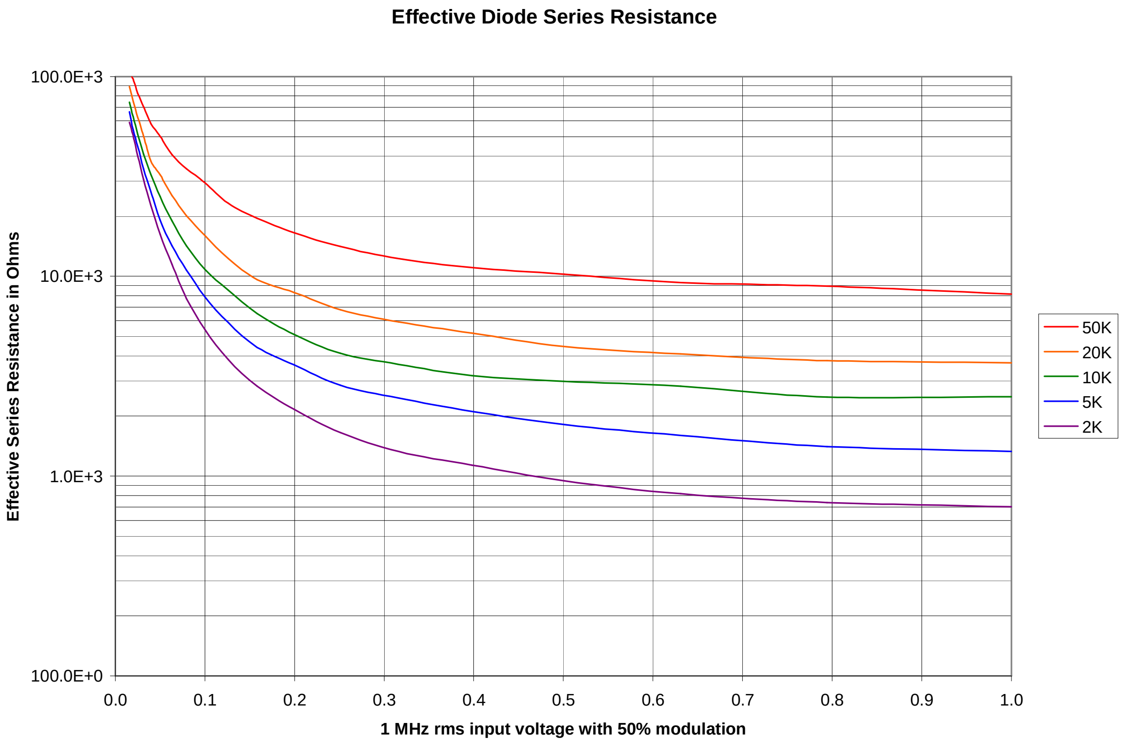


Figure 8: Effective diode series resistance versus applied signal

The effective input resistance to the rectifier circuit is the sum of the load resistance and the diode series resistance. (check factor of 2 for half-wave)

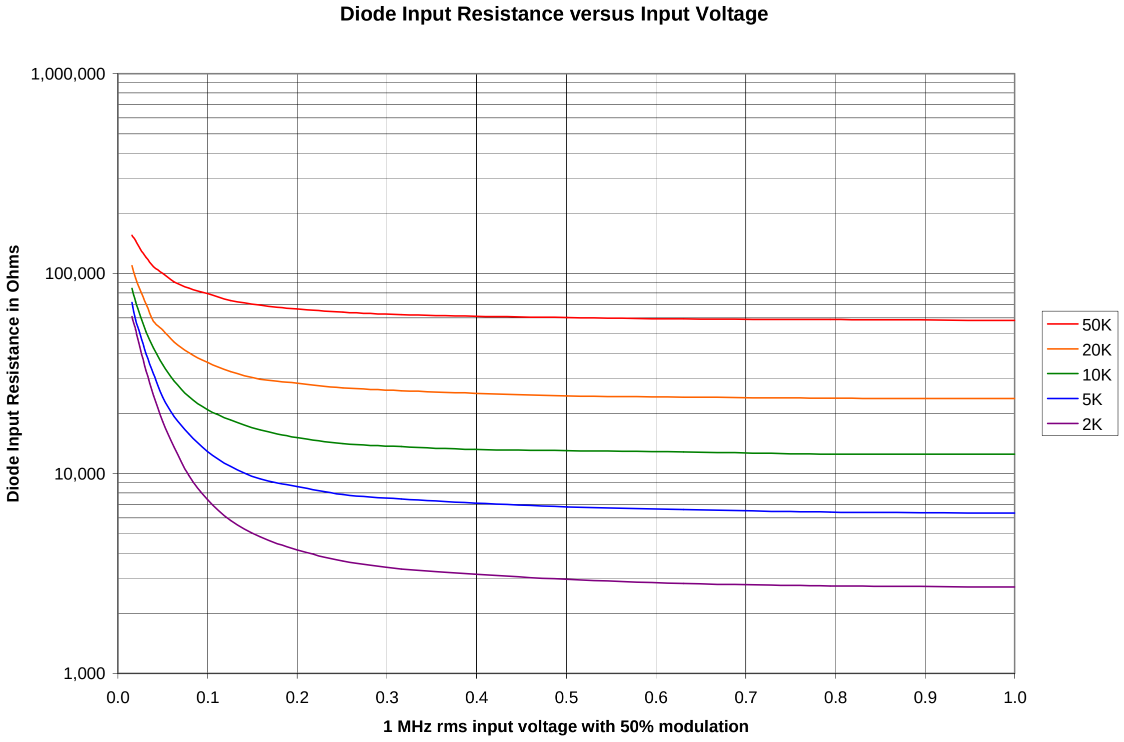

Diode Input Resistance versus Input Voltage
Diode Input Resistance in Ohms
1,000,000
100,000
10,000
1,000
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1 MHz rms input voltage with 50% modulation
50K
20K
10K
5K
2K

Figure 9

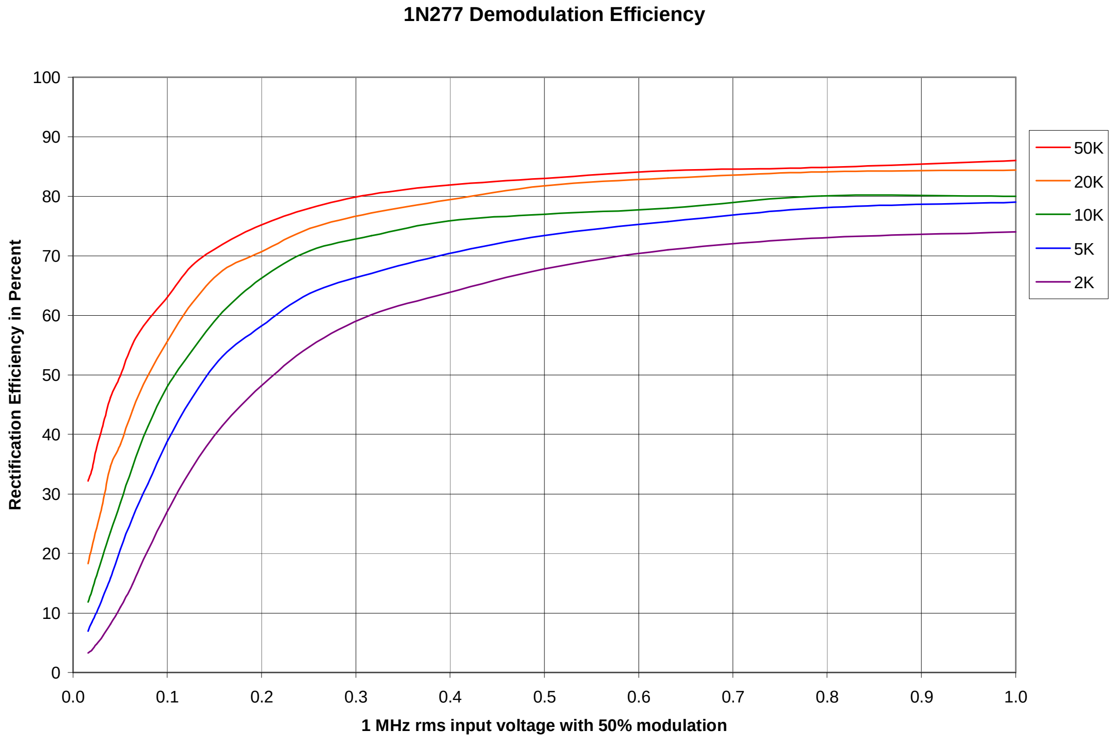

1N277 Demodulation Efficiency
Rectification Efficiency in Percent
100
90
80
70
60
50
40
30
20
10
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1 MHz rms input voltage with 50% modulation
50K
20K
10K
5K
2K

Figure 10: Diode Demodulation Efficiency

Conclusions

For best demodulation efficiency the diode (preferably germanium) should be connected to a high-impedance load and be driven from the highest RF voltage in the system.

References

1. Terman