PIN-Diode Counter

Bernd Laquai 4.9.2012

The BPW34 PIN-Diode

The most legendary PIN-diode which is also used as a nuclear radiation detector is the BPW34. It is available from several semiconductor manufacturers in different variants and was originally designed for visible and invisible wavelength up to the IR wavelength region. Since such a diode is sensitive to light the use as a nuclear radiation detector requires proper shielded against light. The cost of a BW34 diode is generally below 1 Euro.

Fig. 1: BPW34 photodiode from Vishay

The BPW34 shows up with a dark current of typically less than 2nA when it is reversely biased at 10V. This is important when the intention is to detect current impulses in the Nano ampere range. Reverse voltages of up to 30V are possible without causing a breakthrough of the PN junction. However for a low cost battery operation a reverse voltage of 8-12V is preferable.

The capacitance of the diode is important too. It determines how short the current pulses may be to still be able to detect them. A capacitance needs to be charged first before a voltage change can be measured and this takes time. The radiation quants only generate charge carriers for a few nanoseconds therefore the capacitance need to be very small when a voltage change needs to be achieved. In contrast the capacitance becomes larger when the active area of the diode is enlarged just to increase its sensitivity for small amounts of radiation. This means that a good compromise needs to be found when the goal is to detect individual quants of radiation. The capacitance of the BPW34 from most of the suppliers is between 10-50pF depending on the reverse bias and therefore generates voltage changes of several microseconds duration. The active area is 7.5mm^2 which is much smaller than that of most Geiger Muller tubes. Therefore a smaller count rate is achieved even with arbitrarily large amplification of the signal.

Partly the BPW34 diodes can be found with IR filter, which is filtering large amounts of the visible light. This may be helpful too. However the IR radiation is still causing interferences and therefore needs to be blocked when the goal is to be sensitive to only the radioactive radiation. A similar PIN diode is the TEMD5100.

Already published PIN-Diode Counters

The major challenge for a PIN diode counter is the immense amplification required to produce a click from a 50us long and 10nA weak current pulse caused by a single radiation quantum. It is comparatively much simpler to handle a solar cell generating several 100mA from constantly shining sunlight.

On the Internet and in respective hobby electronics magazines many circuit diagram proposals and demonstration examples are described. After the Chernobyl nuclear incident 1986 the German electronics magazine “Funkschau” already published proposals for a diode based Geiger counter (magazine Nr.21, 1986). However the circuit was still very complex with many discrete transistors, since highly integrated circuits were not available at that time.

The German author Burkhard Kainka maintains a webpage with the name elektroniklabor.de where further examples for circuits and experiments can be found. After the Fukushima nuclear incident 2011 he published two examples of PIN diode counters together with its circuit diagram in a magazine named “Elektor”. The first circuit still uses discrete bipolar transistors. The second makes use of an integrated operational amplifier but one junction field effect transistor is still required to achieve the impedance conversion. The article is available in English language on the Internet page of the distributor company named Farnell (Element-14) :

http://www.element14.com/community/servlet/JiveServlet/previewBody/
41953-102-1-229709/Elektor%20Radiation%20Meter.pdf

On international pages even more circuit examples can be found but it is difficult to find professional circuit proposals based on modern integrated operational amplifiers. One example of such a circuit is given in an application note of the semiconductor manufacturer Maxim:

http://pdfserv.maxim-ic.com/en/an/AN2236.pdf

When performing a literature search one should be aware of the fact that the main purpose is to detect very weak signals from very small energy radiation quants. The energy per single radiation quantum is much higher for nuclear radiation compared to photons as with visible sunlight. However, since only a certain minimum energy must be available to operate a PN-junction in photovoltaic mode it is possible to restrict the literature search to applications of photo detectors in the visible and infrared light even though the goal is an application for the all penetrating nuclear gamma radiation. For visible and infrared light detectors the application notes and professional circuit examples in books are more frequent particularly in the area of optical data transmission.

<u>The basic requirements for the electronics in a PIN diode counter</u>

The goal for a PIN diode counter is to generate an audible click (about 1msec and a few mA) in a loudspeaker from the short (50us) and weak (several 10nA) current pulse generated by the diode that indicates a single disintegration (irrespective of the type of nuclear radiation). In other words a current amplification factor of about 100000 (100dB) and a pulse stretching by a factor of about 20 will be required.

Whereas the stretching of an impulse means no challenge to the design, the large amplification is a big challenge. The challenge is not related to achieve an amplification of 100dB but rather the fact that on one hand not only the signal will be amplified but also the noise and interferences and on the other hand the amplified signal may be coupled into the input causing oscillations rendering the whole circuit useless for a normal operation.

<u>Basic architecture of a PIN-diode counter</u>

Typically a PIN-diode counter consists of the PIN-diode as detector, a measurement amplifier, a comparator and a pulse stretching unit. As a converter for the audible signal either an earphone or a loudspeaker is required. In order to generate an optical signal a LED is sufficient perhaps supplemented with a toggle flip flop to store the information of a change.

<u>Operational amplifiers versus discrete transistors</u>

Many older circuit proposals use discrete (single) transistors to implement the measurement amplifier. The many examples and the results show that these types of circuit work perfectly well.

Modern measurement amplifiers however deploy highly integrated operational amplifiers (OP's) containing many transistors integrated into a small amplifier package. Integrated circuits achieve extremely high amplification factors and amplify extremely small voltage differences. The simplest model of such an operational amplifier is a voltage controlled voltage source with infinite gain. A more realistic model is a voltage controlled voltage source with very high gain (up to 10^6) and limited signal bandwidth (up to several GHz).

It is correct to state, that many professional electronic developers quickly make use of readily available integrated circuits to shorten development time, since they can be described with pretty simple models. Furthermore it's not required to check if also a solution with only few discrete transistors would exist too that even would have advantages such as a lower cost of the parts. On the other hand, in the case of the measurement amplifier in the PIN diode Geiger counter the situation is different. A solution with discrete transistors no longer can compete with today's ICs even when a high development effort is spent or the discrete parts are much cheaper. The advantage of today's ICs is mainly related to their size and number of required additional passive parts. The sensitivity of the amplifier and its performance is strongly linked to the length of interconnects and the parasitic effects of the discrete parts that can't be avoided. A small footprint of the circuit is highly advantageous in any case and always should be a key goal.

Today's operational amplifiers require only a minimum number of external parts and come in such small packages such that the circuit size can't be smaller when using discrete parts. Highly integrated ICs in small packages therefore mean less circuit nodes and shorter interconnects with less capacitance. Furthermore the printed circuit board is quickly manufactured when only a few parts are required. Additionally modern operational amplifiers behave almost ideal: input circuits below 1pA, an open loop gain of several hundred thousand and bandwidth up to the Gigahertz range. The power consumption for such a part does not exceed 10mA and it is available at a cost of less than 5 Euros.

However the biggest challenge with today's operational amplifiers is to select the right one from thousands of parts available. Reading and understanding the respective datasheet often is a nightmare. Therefore the main contribution of a good designer is to correctly understand the datasheets and to select the optimal OP.

Signal to noise ratio

In electronic circuits it is inevitable that resistors as well as semiconductors junctions generate noise. As a consequence it is required to get along with the noise. In this respect the main goal is to get the information carrying signal out of the noise such that it can be detected and evaluated. In order to generate a click in the loudspeaker of a Geiger counter typically a voltage comparator is used. The comparator compares the voltage from the measurement amplifier to a known threshold voltage. Only when the difference is significantly larger than zero, a clicking pulse is generated for a certain amount of time.

Normally the radiation quants impinging on the detector surface in different angles and from different distances. Therefore they lose a different amount of energy before ionization occurs. This causes different number of carriers to be generated and therefore different current pulses are generated. No specific signal heights dominate (in contrary to a good semiconductor based spectrometer). With respect to the energy histogram a negative exponential shape quickly becomes visible. This means there are many weak pulses but few strong pulses. In order to count as many pulses as possible, it is desirable to adjust the comparator threshold to a very small value. However the noise imposes a limit to this goal which is present at the input of the comparator even without the signal. Theoretically the noise is distributed according to the Gaussian normal distribution which means that it can get arbitrarily large at a random point in time. In reality however, the distribution is rather bounded, similarly as with tossing ten dice and looking for the distribution of the sum of all pips and its maximum and minimum (10 and 60). Therefore it is possible to adjust the threshold shortly above the bounded noise level to count a maximum of pulses.

As a consequence the ratio of the signal energy to the noise energy (rms values) is a highly important performance number. This ratio can be optimized within some limits by different circuit techniques and the selection of parts. It is named signal-to-noise ratio and is measured in decibels [dB].

The bandwidth

Any signal can be decomposed into periodic sinusoidal signals of different amplitude, phase and frequency (Fourier spectrum). When analyzing the noise with respect to the contained frequencies, it can be realized that thermal noise and the noise from semiconductor junctions shows up with energies at any frequency. The noise power of a truly random noise process such as the thermal noise is even distributed equally over frequency (white noise). Only at very low frequencies below 100Hz 1/f noise or flicker noise appears which increases with reducing frequency. The 1/f noise however needs not to be amplified for the Geiger counter signal. This in turn means that the higher the bandwidth of the measurement amplifier is chosen the higher the noise power gets in relation to the measurement signal and the stronger the noise covers the wanted signal.

The wanted signal at the amplifier input consists of short unpredictable impulses of about 50us duration. This means that the energy of the pulses is distributed at frequencies below 20kHz. Since the pulses occur only sporadically the DC portion of the pulses needs not to be amplified. Therefore the low frequency energies below 100Hz where the 1/f noise is located can be suppressed without major impact on the signal. In order to achieve a good signal-to-noise ratio it is of importance that the bandwidth of the amplifier does not exceed the 20kHz, because above this frequency there is only noise and no signal energy anymore. In total the frequency characteristic of a measurement amplifier needs to have a band pass characteristic with a lower corner frequency of about 100Hz and an upper corner frequency of the pass band at 20kHz. Of course this needs to be adapted in detail to the specific detector type used and may differ slightly. Regarding the selection of the operational amplifiers it is important that they come with a small noise power density per frequency. For the mostly dominating voltage noise the value is given as input referred voltage noise in nV/sqrt(Hz). The voltage noise at the output can be estimated coarsely from multiplying this value with the amplification factor and the square root of the bandwidth.

Interferences

Due to the high amplification required also the smallest interferences are visible at the output. The most dominant sources of interference are capacitively coupled electrostatic fields. Therefore the amplifier needs to be well shielded with a metal housing that protects the amplifier like with a Faraday cage from the electrostatic fields. A plastic housing that just protects the detector from visible light is not sufficient in most cases. However a metal can is appropriate and has the advantage that the ground connection can easily be soldered to the sheet metal (the shielding is most efficient when connected to the ground potential of the circuitry). A protection against magnetic fields is very difficult to achieve but fortunately these types of interferences are rather rare. A certain distance to transformers of course should be kept.

Oscillations caused by feedback

A feedback of signal frequencies to the input by unwanted coupling often leads to oscillations. A requirement for this to happen is a total amplifier gain of more than 1 and a phase shift by 180 degrees for the given frequency. The gain requirement is easily met. In many cases the feedback path is given by capacitive coupling or the power supply connections. The phase requirement however strongly depends on the specific circuitry around the amplifier. The circuitry must be designed in a way that it prevents the phase to be shifted too much from input to output. There should always remain a certain phase margin to the 180 degrees for all amplified frequencies. When the bandwidth of the amplifier is high, the risk for too few phase margin is also high. In critical cases a remedy may be possible by just reducing the amplifier bandwidth.

Comparator and Pulse Stretching

The gain of the amplifier should be adjusted such that the amplified pulses at the output reach a voltage of about 1V and the noise power reaches an rms-voltage of below 100mV in this case.

Such a signal to noise ratio is sufficient to have the comparator to detect the pulses safely. The comparator then shows a voltage swing of almost the full supply voltage when it switches. The comparator can additionally be designed in a way that it stretches the pulses simultaneously to make the pulses audible. When the comparator current is not sufficient to drive a loudspeaker directly, a single discrete transistor can be used to provide the required current. For outdoor applications an earphone connection is advantageous, since a lot of other noises may be around drowning the clicks of a speaker. Further a LED indicator may be helpful for a “quiet mode”. However, when using a LED indicator a toggle flip flop is helpful to memorize a rarely occurring pulse until the next one occurs. A more complex optical display in contrast may significantly increase the power consumption.

Power supply and blocking

It should be a key goal for the circuit to minimize power consumption as best as possible. A 9.6V NiMH rechargeable battery block or a 3 cell Lithium-Polymer battery (11.1V) is recommendable since in emergency situations no primary batteries will be available anymore in the supermarket. In conjunction with a small solar module the power supply will be ensured in such catastrophic cases. The power consumption is low enough when it does not exceed 10mA (the capacity of a 9.6V NiMH block is around 200mAh and would be sufficient for 20h). The advantage of a battery voltage in this range is the possibility of a direct reverse bias of the PIN diodes to reduce its capacity.

The clicking of a loudspeaker may cause significant changes in the supply voltage that under certain condition may couple to the input to the circuitry and cause oscillations. Therefore each stage of the measurement amplifier needs to be well blocked with individual blocking capacitances. Further it is advantageous to connect the measurement amplifier with a low pass power filter (inductance with series resistance and large capacitance) to the power supply to separate it from the influences of the comparator stage. The comparator stage and speaker driver should be limited in rise time with a respective RC filter to minimize supply voltage changes caused by the interconnect inductances.

Test of the circuit

In general it is more advantageous to distribute the gain over several stages and to adjust each stage individually for its partial gain and bandwidth. In such a case each stage can be assembled and validated one after the other and to test it by itself. However it is important to provide an equivalent load of the next stage correctly to the previous stage otherwise the result is not really representative. The use of a high impedance probe is always recommendable since a probe also imposes a significant load to the signal.

The fact that the PIN diode is sensitive to visible light in the first glance appears as a big vice. But this vice can be turned into a virtue for testing purposes. When the circuit is built into a light shielded housing, a regular red LED (not a super bright) can be integrated together with a series resistance of about 10kOhm. If this LED is biased with an offset voltage until it shines very weakly, a small sinusoidal or rectangular waveform of about 10kHz can be superimposed. The amplifier now should amplify the signal from the LED in a more or less undistorted way. For frequencies above 20kHz the signal should be attenuated more and more similar as for frequencies lower than 100Hz.

When a nuclear radiation test probe is used such as an old watch with radium containing pointers and digits, small 50-100us long pulses should become visible from time to time with a maximum amplitude of about -1V at the output of the amplifier. An oscilloscope can easily be triggered to this event. The majority of the pulses however will be below -0.5V and the noise typically will be around 10-50mV rms for state of the art operational amplifiers.