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Application Note

SOLID STATE GAS/SMOKE DETECTOR SYSTEMS

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This application note describes two types of gas/smoke detector systems - semiconductor sensor and ionization chamber. The ionization chamber systems feature an extremely low leakage current MOSFET designed for this application. McMOS is used in some examples to perform the time delay and alarm functions for the semiconductor sensor and end of battery and repetitive alarm indications for the ionization chamber. Complementary discrete circuit techniques are also illustrated for the low standby current requirements of battery operated detectors.

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INTRODUCTION

With the recognition of the need for greater fire safety measures by both industry and government, the fire protective signaling system field is rapidly expanding.

Some of these systems, particularly those that have been in use for many years, detect only heat. Others detect only gas or smoke, and still others, both heat and products of combustion (gas, smoke). The techniques used for detection are varied, ranging from ionization chambers, infrared, photoelectric, thermal and the recently developed heated surface semiconductor sensor.

Each system has its own merits in being able to detect the fire and its products of combustion at the various fire stages. The ionization chamber and semiconductor sensor can detect a fire in the incipient stage during which the invisible combustion gases are formed and also in the smoldering stage where visible smoke is generated. The photoelectric type can detect visible smoke particles either by obscuration of a projected light path or by reflection or scattering of the light from the smoke to a light sensitive element. The third and fourth stages of a fire, the flame and heat stages, can be sensed by infrared and thermal detectors respectively.

Due to the comprehensive nature of this subject, this application note will cover only the ionization and semiconductor sensor systems. The photoelectric, infrared, and thermal detectors, while recognized as viable systems, will not be covered.

Of the two sensors described, the semiconductor gas/smoke detector is readily available[1] and will be of interest to the hobbiest and novice. The ionization chamber sensor is presently not available through distribution. The illustrated circuits are basically design ideas for those who are in this market or who have the resources (including AEC licensing) to design their own chambers.

GENERAL

A smoke detector is a device which is sensitive to airborn products of combustion. These products may consist of gases, ions, water vapor and invisible as well as visible smoke particles.

The basic circuitry for most smoke detectors is relatively simple, consisting of the sensor, a comparator or threshold detector, the alarm driver and alarm. If the sensor is of high impedance, as in the ionization chamber case, a buffer stage is required. The alarm can be audible (horn), visible (lamp), or a relay contact closure for remote indication. The unit may be self contained for single station operation or may consist of several sensors feeding a remote control station.

According to the National Fire Protection Association pamphlet on Household Fire Warning Equipment, the input power may be ac line or battery. Neither loss nor restoration of power shall cause an alarm signal. When line operated, a visual indicator shall show power on. If the smoke detector is battery operated, the unit must operate for at least one year including routine testing. After that period, when the battery voltage drops below the operating value, a distinctive audible alarm sounds, indicating battery end of life. This signal occurs at least once a minute for a period of seven days. The sounding device produces greater than 85 dB sound level at a distance of 10 ft.

SEMICONDUCTOR GAS/SMOKE DETECTOR

This semiconductor sensor, the Taguchi Gas Sensor (TGS), was developed by N. Taguchi and has been marketed since 1969[1]. It consists of an N-type semiconductor of tin dioxide encased in a noble metal wire heater which also serves as an electrode. The operating mechanism is based on the adsorptive and desorptive reaction of gases on the surface of the device. The purpose of the heater is to elevate the device temperature to a fixed value and thus stabilize its operation. When combustible gases such as hydrogen, carbon monoxide or other gases are present in the air, they are adsorbed on the surface of the semiconductor and effectively increase the conductivity of the device. The increased conductivity of the TGS when exposed to even a low concentration of gas can be twenty times its conductivity in air. This change can be readily measured by simply placing the TGS in series with a load resistor and applying an input circuit voltage (ac or dc) to the network. In the presence of gas, the TGS resistance will decrease causing the load voltage to increase. This step voltage is normally high enough to directly trip the comparator and initiate the alarm.

Of the several TGS devices, some are tailored for general purpose gas detector applications and others for carbon monoxide and smoke detectors. These devices can additionally sense hydrocarbons (butane, propane, isobutane, ethane, methane), hydrogen, acetone, benzene, hexane and ethanol to various degrees.

The sensor requires time to reach a stable condition. Depending upon the model type, this stabilization period

Circuit diagrams external to Motorola products are included as a means of illustrating typical semiconductor applications; consequently, complete information sufficient for construction purposes is not necessarily given. The information in this Application Note has been carefully checked and is believed to be entirely reliable. However, no responsibility is assumed for inaccuracies. Furthermore, such information does not convey to the purchaser of the semiconductor devices described any license under the patent rights of Motorola Inc. or others.

can vary from 1½ to 5 minutes. If the TGS were unpowered for any appreciable time, and power reapplied, the initial resistance will be lower than normal, causing a false high output voltage that trips the alarm. To inhibit this false alarm, a lockout time delay circuit can be incorporated.

SIMPLE SCR GAS/SMOKE DETECTOR

A very simple, inexpensive, gas/smoke detector using the TGS308 semiconductor sensor and an SCR for half-wave controlling an ac horn is illustrated in Figure 1.

The TGS sensor in series with the 2 k ohm threshold control potentiometer R1 is powered by the prescribed 1.2 v rms heater voltage and 30 v rms circuit voltage (manufacturers specified range: 5 to 30 v). When no gas is present, the output voltage (across R1) is approximately 3 v rms. When the sensor detects gas or smoke, the output voltage will rise due to the decrease in resistance of the sensor to some value proportional to the gas concentration, typically 20 v in large concentration.

This signal is tapped off the threshold control potentiometer (to vary sensitivity), and rectified and filtered to provide dc gate control of the SCR. The fired SCR half-wave powers the ac horn with approximately 21 v rms ($e_{rms} = e_{peak}/2$).

The SCR will remain fired as long as the gate is biased on. Once the gas or smoke has cleared the sensor, the SCR will commutate off when its holding current is reduced to zero.

In order to prevent the SCR from drawing excessive leakage current and thus increase dissipation when the anode goes negative concurrent with positive gate voltage, diode D2 is required.

The sensitive gate SCR MCR106-3 allows for elevated temperature operation with no heat sink when powering the typically 24 v rms, 475 mA horn. This 4A rms device can sustain a 55°C ambient temperature when operated at 0.5A average current and at a 180° conduction angle.

Although extremely simple in design, this circuit does have disadvantages:

1. No time delay to prevent false alarm when power is turned on.
2. Requires a custom transformer.
3. Although the half-wave operation of the horn is appropriately alarming, its sound level output is reduced.

TGS GAS/SMOKE DETECTOR – TRIAC FULL-WAVE CONTROL

To take full advantage of the sound output of the ac horn (85/90 dB at 10 feet), the horn can be full-wave triac controlled as shown in Figure 2. This circuit is similar to the SCR one, the basic difference being the addition of transistor stage Q1. This transistor supplies the worst case gate trigger current (20 mA for II and III quadrant triggering at -40°C) for the 2N6070A sensitive gate triac. As in the previous example, a custom transformer is required which must supply the 1.2 v, approximately 500 mA heater current, in addition to the circuit voltage of 24 v.

TGS GAS/SMOKE DETECTOR – McMOS LATCH

A circuit that provides the required inhibit time delay for TGS gas/smoke detectors is described in Figure 3A. By using one McMOS quad 2-input NOR gate MC14001, the approximate two minute lockout period and the other

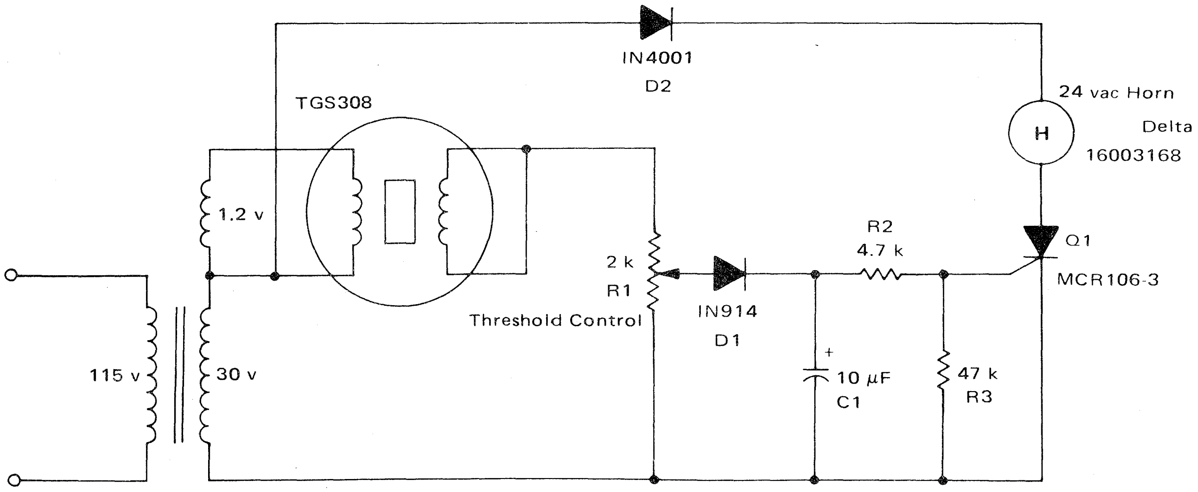

FIGURE 1 – Simple SCR Gas/Smoke Detector – Half-Wave Control

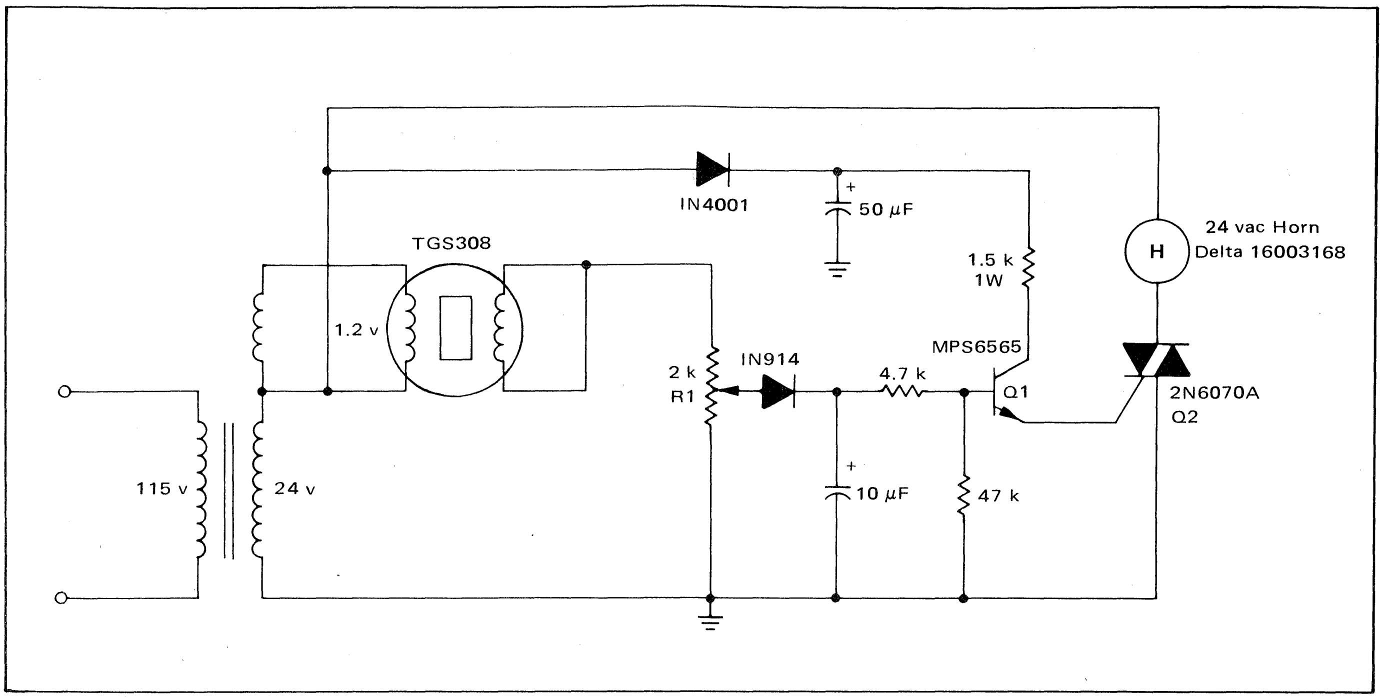

FIGURE 2 – TGS Gas/Smoke Detector – Triac Full-Wave Control

required functions of buffered input and alarm latch can be implemented.

This circuit uses a standard 12.6 v C.T. filament transformer (>500 mA) to provide heater power, circuit voltage for the TGS308 and power for the electronics. Resistor R1 is used to drop the 6.3 v winding down to the 1.2 v heater. Incorporated in this network is the LED D5 to indicate power-on.

When smoke or gas is present, the ac output voltage increases and is rectified, filtered and applied to one input of 2-input NOR gate 1. Diode D2 and the threshold control R4 ensure that the no gas output level will not cause gate 1 to erroneously change states.

The two minute time delay is provided by the C5-R10 network which is connected to one of the high impedance inputs of gate 2. When power is first applied, a positive voltage step is coupled to the input of gate 2 forcing its output low. This, in turn, inhibits the latch flip-flop (gates 3 and 4) from being set, regardless of the state of the sensors. Gate 2 output will be low for the time required for time delay capacitor C5 to charge. The time delay depends on the tolerance of the timing components, the leakage resistance of the capacitor and the threshold tolerance of the McMOS gate. When C5 charges fully, the gate input will be low and the state of the sensors output will control the latch.

The latch, set with a high input to gate 3, causes the output of gate 4 to go high. This McMOS gate output can source the approximate 100 µA to the base of NPN horn drive Darlington transistor, turning on the alarm, and still maintain the required high-level output to latch gate 3. The latch is reset manually by push-button switch S1 to turn off the alarm. The R11-C6 network ensures that the latch will be in the proper state when power is first applied.

False alarms can be annoying when the system has to be manually reset. To overcome this condition, an automatic reset circuit may be desirable (Figure 3B). This variation of the latch circuit automatically resets after approximately 30 seconds by virtue of the timing feedback network R13, C9 and D8. When gate 4 output goes high (alarm condition), capacitor C9 starts charging. When the threshold of gate 4 is reached, the output switches states. The circuit will thus be reset when triggered by a short, false alarm, but will remain latched for as long (plus 30 seconds) as a true alarm is present.

DC power for the circuit is simply derived from the rectified transformer output. The 12 V for the horn is obtained from the lightly filtered, rectified output of the full 12.6 v winding and the McMOS supply from the 6.3 v tap. This independent, lower voltage McMOS supply (approximately 6 Vdc) ensures complete isolation of the two circuits and also allows lower system threshold capability. Resistors R5 and R6 set the supply voltage and also limit the McMOS current when the time delay circuit slowly goes through the linear region of the McMOS device.

The circuit is shown driving two different types of horns. The Delta interrupter contact dc horn requires approximately 60 mA average current which mechanically vibrates the horn diaphram at about 500 Hz. This produces a sound output level of 85 to 90 dB.

The initial peak start-up current may be as high as three times the repetitive peak current (approximately 120 mA); a value well within the drive capability of MPS-A13 Darlington (h_{FE} Min = 10,000).

One note of caution should be mentioned when using this horn in hazardous gas environments – the TGS will detect combustible gases. It is conceivable, although experimentation has not proven it to be the case, that the spark associated with an inductive, interrupter contact device could have enough energy to initiate an explosion.

If the detector system is to be used in such an environment, it is recommended that other types of horns be used. The Mallory SC628 has no contacts and is free from arcing. This device requires approximately 6 mA at 12 Vdc and produces a 2.9 kHz tone at a sound output level of 68 to 80 dB (70 dB typ). When using this horn, the extremely high current gain of Q1 is not required. This transistor can be replaced with a 2N3904, whose new base resistor R12 should be 22 k ohms. This results in a base current of approximately 200 μA and a forced beta of 30.

If the alarm sound level is not considered sufficient, then an ac horn can be used as described in the following system.

TGS GAS/SMOKE DETECTOR, McMOS-TRIAC FULL-WAVE CONTROL

A system using a McMOS gated oscillator that directly interfaces with a triac controlled ac horn is shown in Figure 4. This circuit uses the MC14572 hex gate (four inverters, one 2-input NAND gate and one 2-input NOR gate) to provide the complete gas/smoke detector logic functions, i.e. time delay, gated astable multivibrator and buffers.

The 2N6070B sensitive gate triac uses negative gate current triggering of -15 mA (quadrants II and III) for maximum sensitivity at low temperatures. To sink this current from the triac gate requires the McMOS drivers to be operated with a negative supply ($V_{DD} = 0, V_{SS} = -15$ V).

This -15 V power supply is derived from the 24 v tap of the power transformer and is rectified, filtered, zenered and current limited by resistor R6. This limiting is required to prevent excessive device current from flowing when gates 1, 3 and 4 operate in their linear regions.

The 15 V supply was chosen for greater McMOS output current sink capability. Thus, the two parallel inverter gates 5 and 6 can adequately sink the 15 mA worst case triac gate trigger current (7.5 mA each).

Similar to the previous examples, the TGS output signal is rectified, filtered and zener diode coupled (D2 for thresholding) to the sensitivity control R3. Under no gas condition, the output will be approximately zero volts (high) and when gas is present, the output will be a negative value (low) sufficient to overcome the threshold of McMOS gate 2 and D2.

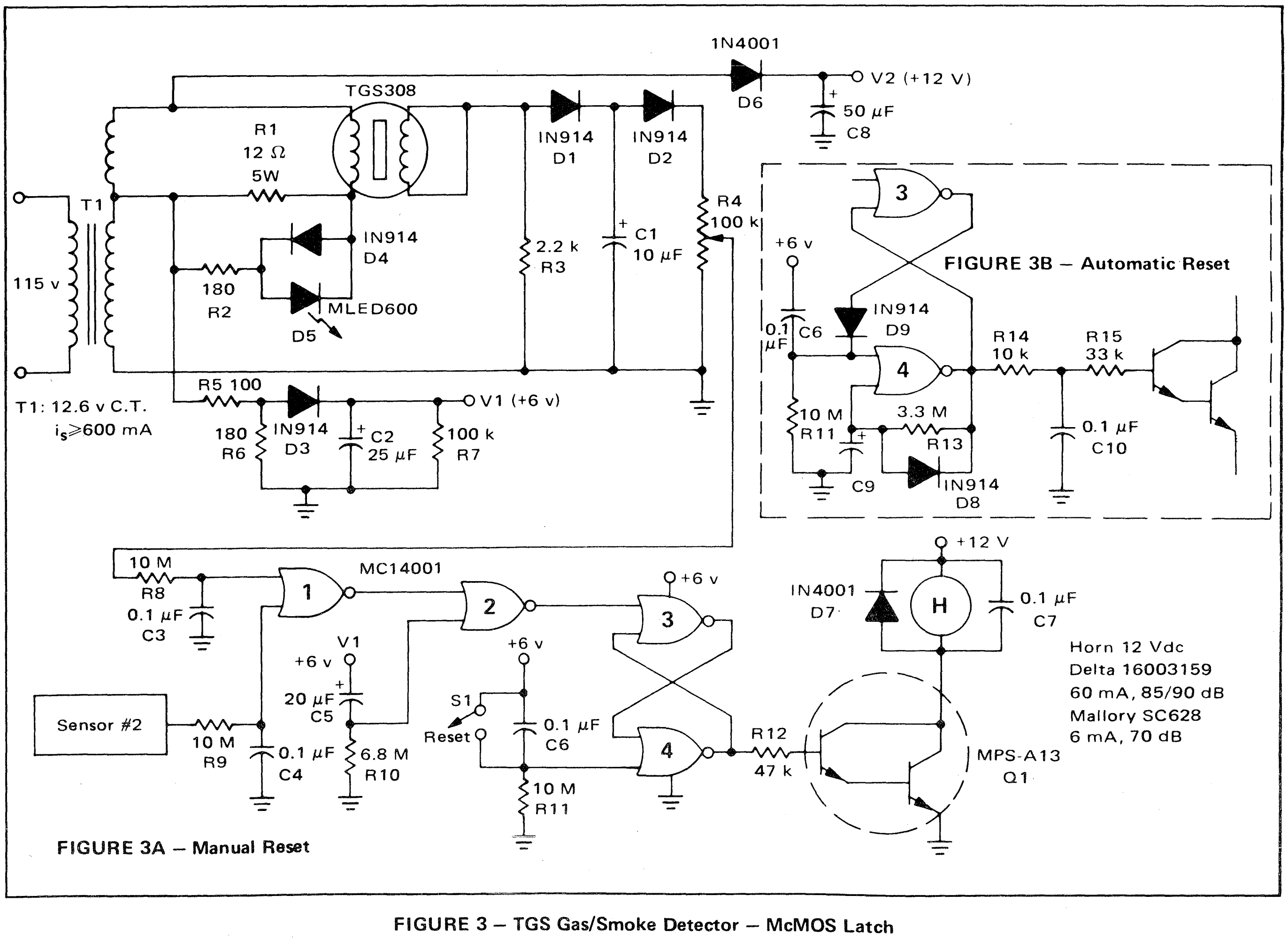

FIGURE 3 – TGS Gas/Smoke Detector – McMOS Latch

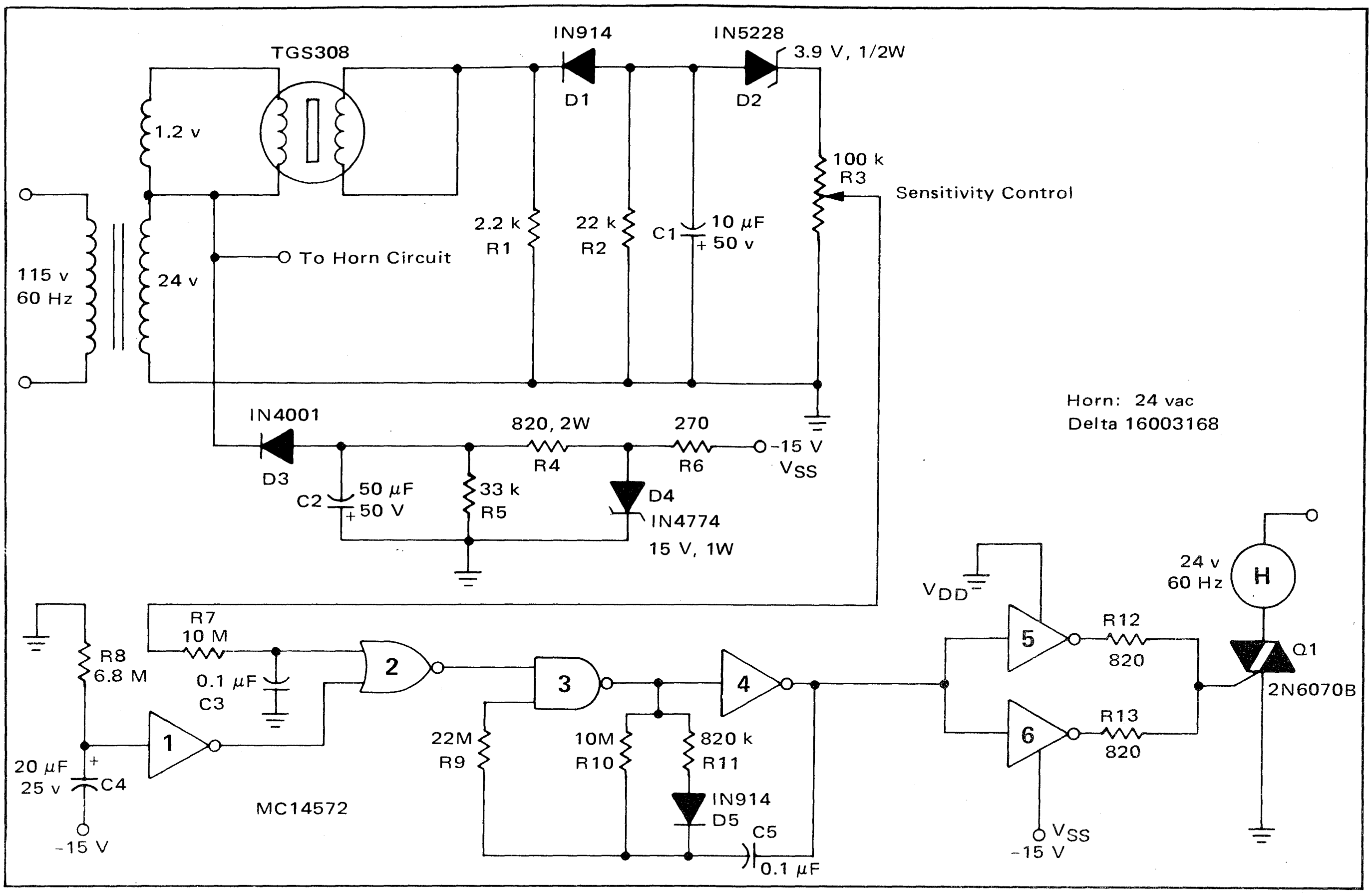

FIGURE 4 – TGS Gas/Smoke Detector, McMOS-Triac Full-Wave Control

During the stabilization time delay period, timing capacitor C4 will be low (below gate 2 threshold) causing the output of the two input NOR gate 2 to be low independent of the state of the sensor output, thus preventing power turn-on false alarms. When C4 has charged, the TGS output will control the state of gate 2 output.

Gates 3 and 4 and the associated resistors, capacitor and diode comprise a CMOS astable multivibrator. The charging and discharging paths for the single timing capacitor C5 are unequal (due to D5) resulting in a nonsymmetric output. This signal is inverted by the triac drivers (gates 5 and 6) to fire the triac and power the ac horn. The distinctive, repetative alarm is on for the astable timing of approximately 2.5 seconds and off for 0.2 second.

Although the horn and triac are shown powered by the 24 v transformer winding, this circuit can just as easily be line powered. A 110 v horn (Delta 16003109) requiring only 55 mA can now be powered by the small signal, TO-92 triac MAC93-4.

IONIZATION CHAMBER SMOKE DETECTOR

Ionization chambers in conjunction with vacuum tube amplifiers have been used as combustion gas detectors for many years, but due to the size and power requirements of the electronics, were not too attractive a system. With the advent of extremely low leakage current MOSFETs and low standby current circuit techniques, this type of detector can now be inexpensively implemented in small, battery operated systems.

An ionization chamber consists essentially of two electrodes. One electrode is the metal enclosure of the chamber and the other, a collector electrode, extends into the opening of the chamber. A minute amount of radioactive material emitting alpha particles is placed in the chamber, bombarding the air molecules and causing it to ionize. When a potential is impressed across the electrodes, the attracted ions will produce an extremely small current in the 10 to 30 pA range. When the primarily invisible products of combustion enter the chamber, they tend to attach themselves to the ions. The enlarged agglomerate ions slow down in the electric field, reducing the particle collection on the electrode and thus reducing the current.

If the ionization chamber is placed in series with an extremely high impedance reference device and a dc voltage applied across the two elements, a voltage divider is created. As the current is decreased due to gas or smoke reaction, the voltage across the reference element will decrease which can be detected by the comparator. In some applications, the reference element is an extremely high impedance resistor comparable in magnitude to that of the ionization chamber (200 to 400 k M ohms).

A second chamber having a similar ionization source, but restricted to gas entry, can also be used in place of the reference resistor. This chamber will theoretically track the first chamber during ambient changes and thus compensate for these variations.

The standby current through the chamber and reference element is typically 20 pA. In order to measure the change of voltage at the reference node due to the decrease in current when smoke is present, an extremely high input impedance buffer stage is required. The input leakage current should be at least a magnitude lower than the chamber current to prevent loading of this circuit.

Motorola has introduced two MOSFETs especially designed for ionization chamber smoke detectors with extremely low leakage currents. The first, the MFE824 depletion-enhancement mode N-Channel MOSFET has a gate reverse current I_{GSS} of 1.0 pA maximum. The second, the MFE823 enhancement mode P-Channel MOSFET also has a 1.0 pA leakage current.

IONIZATION CHAMBER SMOKE DETECTOR #1

Battery operated ionization chamber smoke detectors, in addition to performing the alarm functions, must have a circuit to generate a unique alarm when the battery has reached its end of life. Such a circuit using the McMOS MC14572 for two alarm oscillators (smoke and low battery) is shown in Figure 5. This circuit additionally uses five discrete transistors for buffers and comparators.

Since this battery operated circuit must perform for at least one year, the standby current must be very low. As an example, a 750 mA hour battery would supply an average current of 85 μA for a period of one year. To achieve this low current, the linear circuits are designed at low standby currents and the switching stages are normally off. Using McMOS and low current techniques, as described below, a standby current of approximately 75 μA results.

The front end of the illustrated smoke detector consists basically of a MOSFET-bipolar differential amplifier with the MFE824 (Q1) being the high impedance buffer and the NPN transistor 2N5088 (Q2), the comparator.

The reference resistor R1 is selected to be approximately equal to that of the ionization chamber no smoke impedance, thus setting the voltage at the FET gate to about +6 V (half supply). At the approximately 30 μA FET source current, the V_{GS} of this N-channel MOSFET is about 2 V which places the source at 8 V. Depending on the required smoke detection sensitivity, the threshold control R6 is set so as to back-bias Q2 (500 mV typical), the low current high h_{FE} transistor.

For the chamber used, a 2 and 4% smoke obscuration test resulted in a negative voltage shift at the MFE824 source of about 2 and 3 V respectively. This decreasing FET source voltage turns on Q2 and the following PNP transistor Q3, thus applying a logic one to one input of the 2-input NAND gate 1. The astable multivibrator (gates 1 and 2) is now enabled and the circuit will generate the smoke alarm timing cycle. This non-symmetrical signal (due to diode D1) is buffered through inverter 3 to furnish the approximate 4 mA worst case base current for

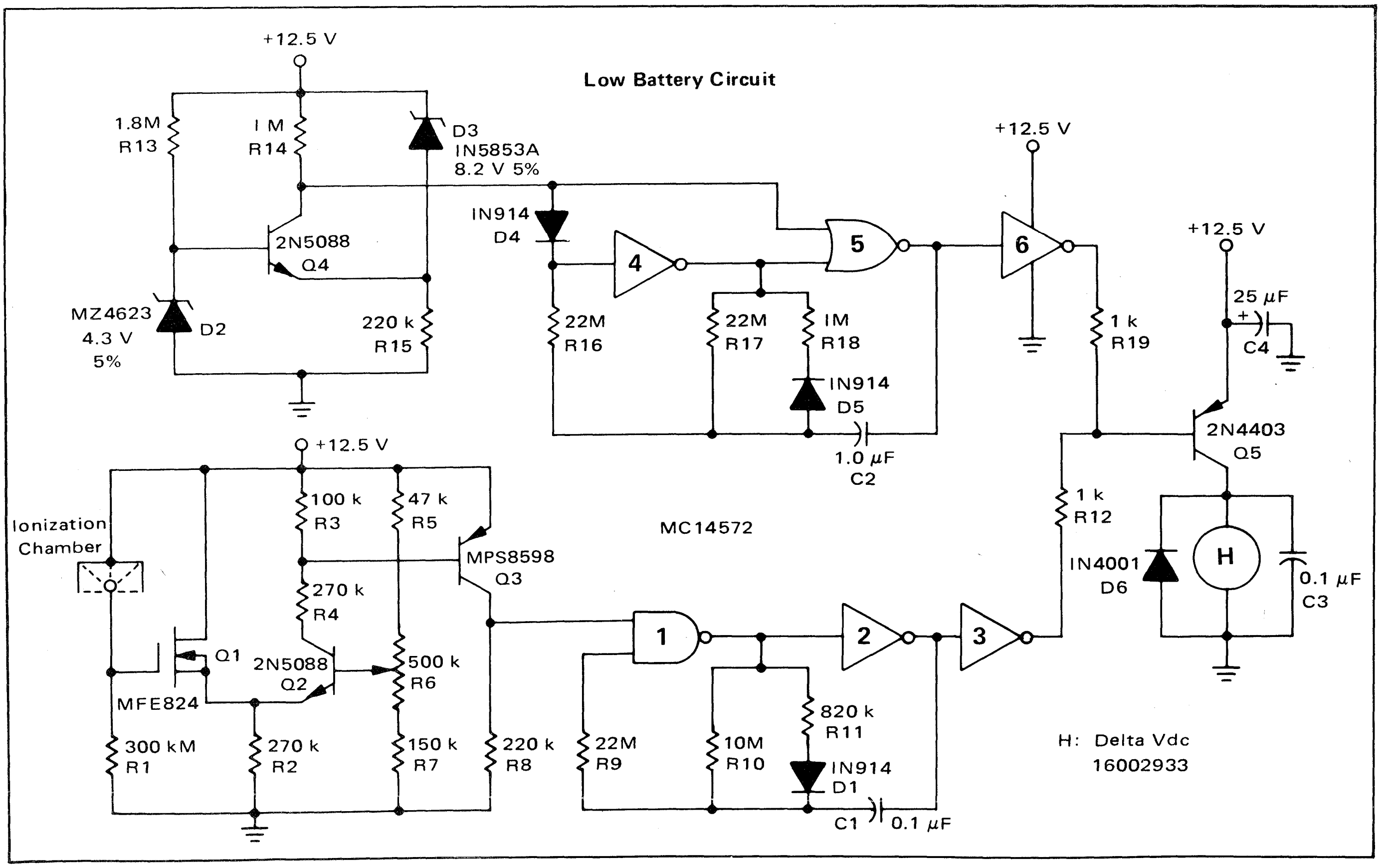

FIGURE 5 — Ionization Chamber Smoke Detector #1 —McMOS Oscillators

the output PNP transistor 2N4403 (Q5) horn driver. The horn is energized at the repetitive astable rate of approximately 2.5 seconds on and 0.2 second off and will sound this alarm as long as smoke is present. This pulsating alarm signal may be advantageous over a continuous signal in some noise environments.

To determine when the battery is low, a comparator consisting of an NPN transistor Q4 and two zener diodes (D2 and D3) is used. To conserve battery power, the reference 4.3 V zener (D2) is operated at approximately 5 μA resulting in a base reference voltage of about 3 V. The 8.2 V zener (D3) is used to couple the full change in battery voltage to the comparator transistor emitter producing a sharp threshold. With the zeners shown, the comparator trips at approximately +10.5 V low battery voltage. Once fired, this transistor saturates placing the collector at approximately +2.5 V, a value below the threshold of NOR gate 5. Diode D4 ensures that the low battery astable multivibrator inverter 4 is in a controlled state under normal battery operation and thus not drawing excessive current due to possible linear operation. When the control input to NOR gate 5 goes low, the astable multivibrator is enabled and its buffered output (through inverter 6) is resistively ORed to horn driver Q5. The dc horn is powered at the astable rate of approximately 1 second every 23 seconds resulting in an average horn current of 60 mA/23, or 2.6 mA. An additional 0.5 mA average current is drawn during the linear operation of the astable multivibrator. This distinctive alarm forewarns the user to change the battery.

IONIZATION CHAMBER SMOKE DETECTOR #2 – DISCRETE VERSION

The previous example used two CMOS oscillators to generate the two alarm signals. If the smoke alarm signal is a continuous one rather than pulsating, then the slightly less expensive, all discrete transistor version of Figure 6 may be used. The standby current for this discrete smoke detector is approximately 70 μA.

The smoke detector front end (Q1, Q2 and Q3) is identical to that of Figure 5. When Q3 now turns on, it supplies 100 μA base current to the Darlington Q4 (MPS-A14). The worst case, low temperature h_{FE} of approximately 5000 for this transistor ensures that the transistor is fully saturated during the horn start up peak current condition. The horn will be powered continuously for as long as the smoke content exceeds the detector threshold setting.

The low battery circuit performs the same function as that of the previous circuit – a transistor comparator

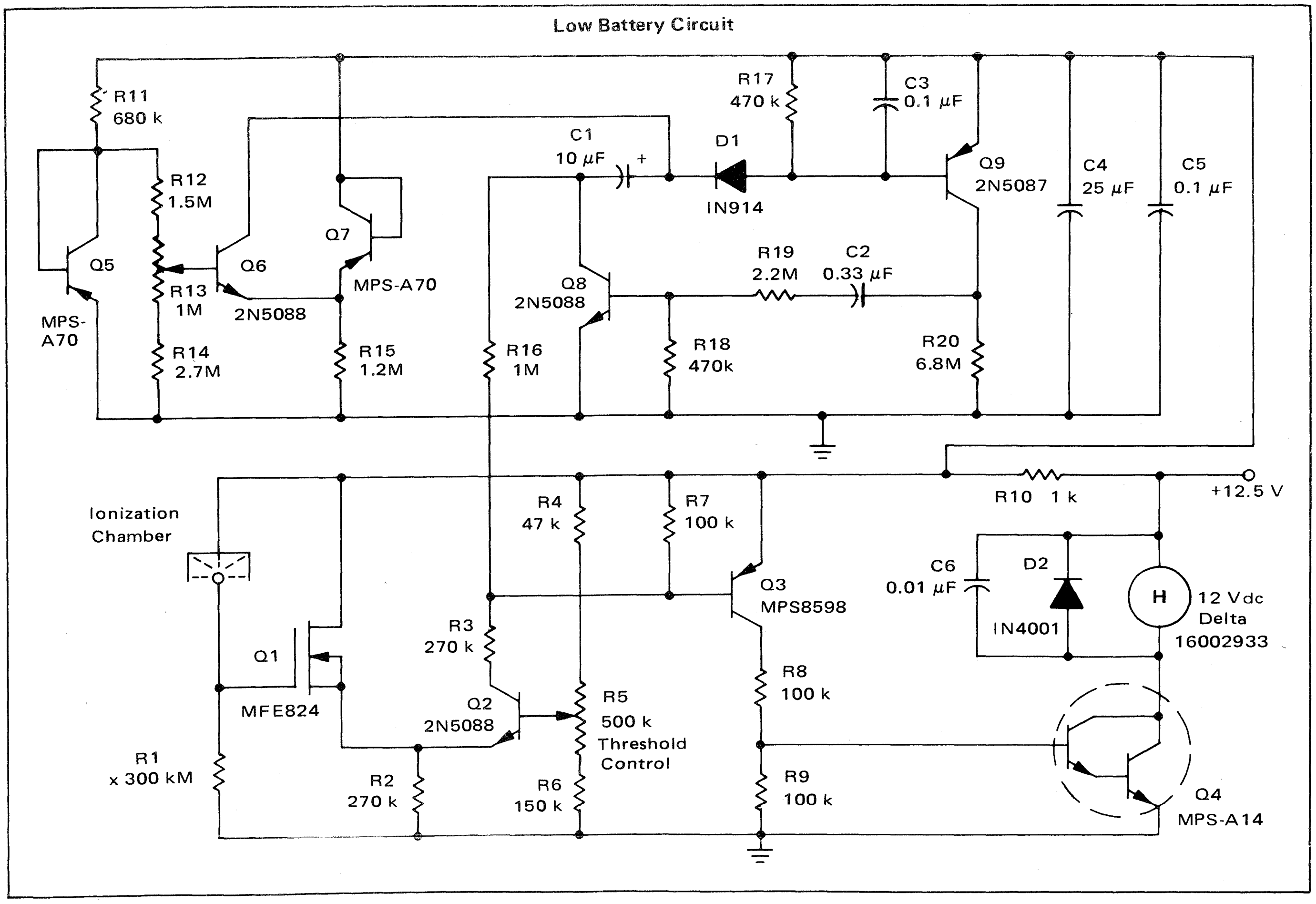

FIGURE 6 – Ionization Chamber Smoke Detector #2 – Discrete Version

enabling a low duty cycle, long time duration astable multivibrator (Q8 and Q9).

The comparator transistor Q6 serves two purposes: one, as a threshold sensing device and two, as a constant current timing source for the enabled, complementary astable multivibrator. The reference and coupling zener functions are now achieved by using the emitter-base junctions of inexpensive, plastic transistors operating in the avalanche mode. These transistor junctions (Q5 and Q7) have predictable avalanche voltages (7 V ± 10%) that sharply zener at currents as low as 1 μA. The low battery potentiometer R13 allows a voltage selection range of 9.8 to 11.2 V with a midrange, typical setting of 10.5 V.

When the battery voltage drops below the threshold setting, transistor Q6 conducts and furnishes a constant current of approximately 3 μA (V_{EQ6}/R_{15}) to capacitor C1. In the off state (Q6 non-conducting), both stages of the multivibrator are off and the only currents flowing are the low device leakage currents (0.1 μA max). Once enabled, the multivibrator will oscillate at approximately a 0.7 second on, 50 second off rate. The output from Q8 then drives Q3 and, consequently, the horn at the same rate. With this duty cycle, the average horn current is 60 mA (0.7)/50 or 0.84 mA.

CONCLUSION

There are several types of gas/smoke detectors in the fire protective signaling system field. Examples of two types, the semiconductor sensor and ionization chamber, are described.

The semiconductor gas/smoke detector, due to its relatively large heater power requirements, is line operated. For false alarm free operation, a time delay stabilization period is usually required. McMOS IC's can readily be used to perform this function and also the other functions (alarm drivers, buffers) for gas/smoke detectors.

The extremely high impedance of an ionization chamber lends itself to battery operated smoke detector systems. To buffer the chamber, a MOSFET (MFE824) with gate reverse current (I_{GSS}) of less than 1 pA is required. Additionally, the standby current for one year operation and for low battery indication is very low. Both McMOS and complementary transistor designs are illustrated to show these requirements.

ACKNOWLEDGMENT

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