Wiegand wire: new material for magnetic-based devices

Switching properties of specially-treated magnetic wires can generate pulses of up to 500 millivolts, with amplitudes unaffected by speed of operation, and no electrical power needed for most applications

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☐ About 10 years ago, John Wiegand discovered that by properly work-hardening a magnetic wire, it is possible, along the exterior "shell" of the wire, to produce a coercive force significantly greater than the coercive force in the wire's core. By virtue of this magnetic differential, and depending on certain external conditions, the direction of magnetization in the core of the wire can be the same or opposite to that in the shell. And switching from one state to the other is easily and repeatably induced at well-defined magnetic-field levels.

Short lengths of wire exhibiting the Wiegand effect can serve as the heart of magnetic pulse generators that have distinct advantages over similar devices, including non-contact operation and a facility for being "read" by detection devices having virtually no input power. Other important advantages are that pulse signals are not rate sensitive, meaning the amplitude of the pulse signal remains the same regardless of speed of operation; they offer any combination of pulse-generation direction and polarity, that is, uni-directional or bi-directional, unipolar or bipolar. Thus any combination of direction and polarity are available for pulse generation. And such devices are capable of withstanding severe environments, including temperatures from -95°F to +300°F.

Over the years, Wiegand has developed material composition and work-hardening procedures to a point where brief pulses (10^{-4} duration) at levels of 2 milliwatts can be produced. With properly-designed detectors, peak voltages of 500 millivolts in the 50-ohm load have been observed.

Domains are oriented

While switching is not a new application for magnetic devices, the Wiegand effect introduces new capabilities in a variety of applications. There is now, for example, a credit-card reading device that needs no electrical power input into the read head. Also possible are a Wiegand-encoded key, a non-contact switch, a flowmeter that's bidirectional and impervious to severe environmental conditions, and a rotary pulse generator that causes no wear on the read head—to name a few. These are being developed under the registered trademark SNMW, for self-nucleating magnetic wire.

Before considering the operation of the Weigand effect, it would be well to review a few properties of magnetic materials. In a "demagnetized" material, illustrated in Fig. 1(a), different regions or "domains" in the material have their magnetizations oriented in different directions, with domain walls separating them. The aggregate magnetization, M, in this state, is zero. By applying a magnetic field, H, to a magnetic material a net magnetization process occurs in three phases. Initially the domain walls move but are reversible, that is, if the magnetic field is removed, the domain walls will return to their original positions. In the next phase, the domain walls move irreversibly. Eventually the domain walls in effect disappear, as in Fig. 1(b), and the direction of the magnetization is uniformly in the direction of the field (c); this third phase is called magnetization rotation. The magnetization process is shown in Fig. 2.

If the magnetization process is reversed, the material will not return to its original magnetic condition. Instead, as the magnetic field is reversed, the magnetization passes through zero at a value called the coercive force field. The resulting plot of $\overline{M}$ versis $\bar{H}$ is called the hysteresis loop, as shown in Fig. 3.

Geometry considered

In a sufficiently large magnetic field, the magnetization, $\overline{M}$, of the material is oriented into the direction of the magnetic field and the material is said to be saturated. Magnetic "poles" are formed on the surfaces of the material in a familiar pattern (Fig. 4). The pole distribution will establish a magnetic field that is opposite to the direction of the material's magnetization. If the external applied magnetic field, $\bar{H}$, is removed, the magnetic field produced by the pole distribution will tend to demagnetize the material. In a permanent magnet, the magnetization maintains its polarization because the internal coercive force field of the material is larger than the demagnetization field.

Closing the loop

Readers interested in discussing the Wiegand-effect technology and its applications may call Milton Velinsky, who heads product development for Wiegand Electronics. Days: July 16 and 17, 9 a.m. to 5 p.m. Number: (201) 291-3818.

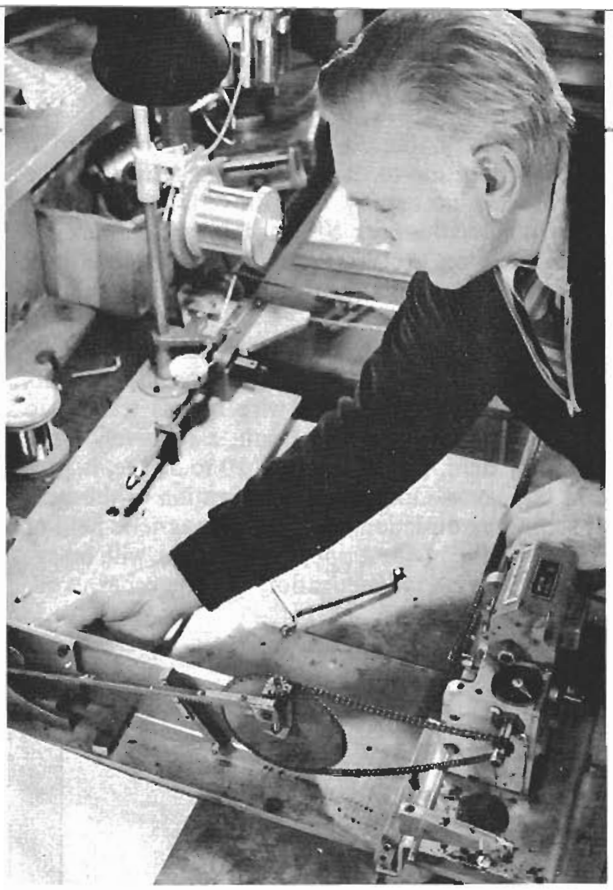
Who's John Wiegand?

The man who has devoted much of his life to magnetics and who discovered and exploited the effect bearing his name, is neither an engineer nor a physicist. He's a musician by training, but instead of music, he chose to devote himself to the application of magnetics.

Born in Germany in 1912, John Wiegand came to the United States in the 1930s and studied piano and choral conducting at the Juilliard School of Music in New York. While attending Juilliard he became interested in audio amplifiers and later became an engineering assistant for magnetic amplifiers at the Bell Telephone Laboratory.

These moves set Wiegand on a different course than music. In 1944 he began working for Sperry Gyroscope Co., Lake Success, N.Y., and later for a Government contractor as a product developer of tape recorders. In 1965 he began to pursue the magnetic research that led to the development and patenting of the Wiegand effect. He has been issued 13 U.S. patents and has several more U.S. and foreign patents pending, all dealing with magnetics.

When Wiegand began his independent research he was joined by Milton Velinsky. Together they organized Wiegand Electronics to develop product applications for the Wiegand effect. Velinsky's primary responsibility has been in arranging licensing agreements with manufacturers.



The strength of the demagnetization field will depend on the geometry of the sample. A thin flat disk has a strong, uniform demagnetization field. As the ratio of the width to the length of the magnetic material decreases, the demagnetization field at the center of the sample gets weaker although it is still quite strong near the end faces (Fig. 4).

In an ellipsoidally shaped piece of material, the demagnetization field is uniform throughout, and for a sample magnetized along the ellipsoidal axis the magnitude of the demagnetization field is given by

$$H_D = 4\pi NM \qquad (1)$$

where N is the demagnetization factor of the ellipsoid.

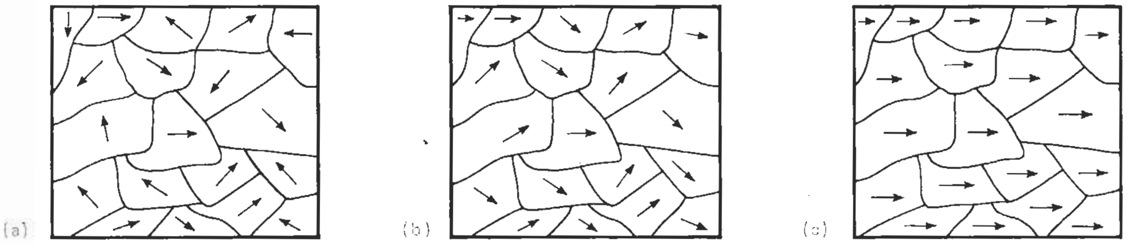
For non-ellipsoidal geometries, the demagnetization field is not uniform and can only be approximated. For wires, the demagnetization field at the center of a sample will depend on the solid angle subtended by the face of the bar from the central point of the wire. For the wire shown in Fig. 5, the solid angle will be proportional to the ratio d/L and the demagnetization field can be approximated by the expression

$$\bar{H}_D = -c(d/L)\,\bar{M} \qquad (2)$$

where c is a proportionality constant somewhat less than 4π. This relationship is accurate to within 5% when L/d is greater than 10. In the wires used for the Wiegand effect, $\bar{M}$ is 1,000 gauss and L/d is about 100 for a wire one centimeter long. The resulting demagnetization field at the center of the wire is about 10 oersteds.

As noted earlier, this field is responsible for the demagnetization of a saturated material when the external field is removed. However, in a long wire, L/d = 1,000, the demagnetization field at the center of the wire is negligible.

If the wire is placed under tension, an internal coercive force field provides a stable state of magnetization when the magnetization lies parallel to the axis of the



1. Three states. Domain arrangements for a polycrystalline material, such as Permalloy, are drawn for simplicity as if each crystalline contains a single domain. In the demagnetized state (a), domains are oriented randomly. As a magnetic field is applied, the domains begin to orient in the direction of the applied field, as in (b). In (c) a saturated state is achieved wherein the domains are uniformly in one direction. In a Wiegand wire, the core magnetization remains in the phase represented by (b), but the net magnetization can be switched back and forth.

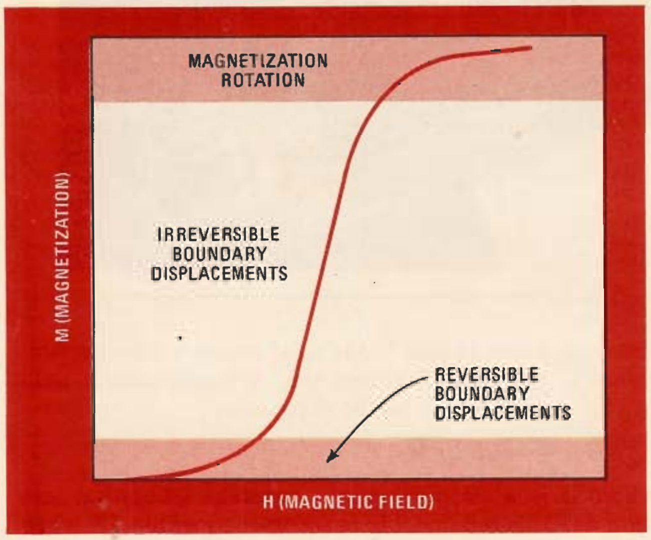
wire. On the other hand, if a magnetic field is applied in the direction opposite to that of the magnetization, the reversal process occurs by domain-wall propagation. Traveling at velocities near 10^5 cm/s, these complex domain walls take on the characteristics shown in Fig. 6. At this velocity the switching time is very short and the peak power is high.

In the Wiegand effect, this magnetization-reversal process is coupled with some unusual physical properties imparted to the wire. The wire first is treated to work-harden the outside. As a result, a relatively large coercive force field, on the order of 20 to 30 Oe, is produced in this layer. Once the magnetization of the wire shell is set in one direction, an applied magnetic field of more than 30 Oe in the opposite direction will be required to reverse its magnetization. On the other hand, the inner core has relatively low coercive force and can be reversed in a magnetic field of less than 10 Oe. During the magnetization process, the core switches by domain-wall propagation as discussed above, but now the shell region of the wire remains unchanged. When the shell and core are magnetized in the same direction, the wire is magnetized. When they are in opposite directions, a permanent cylindrical domain wall exists and the wire is in a demagnetized state.

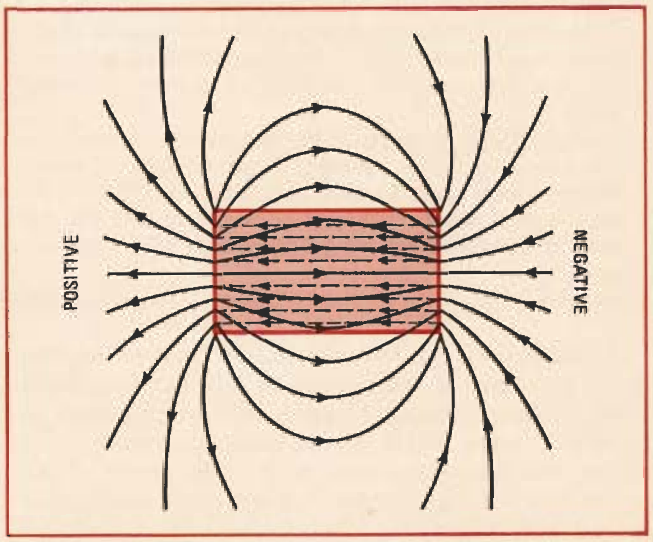
Set and reset

In a short wire of 1 centimeter the demagnetization field is on the order of 10 Oe and will shift the magnetization loop or Wiegand loop to either side of zero, depending on the state of the magnetization in the shell.

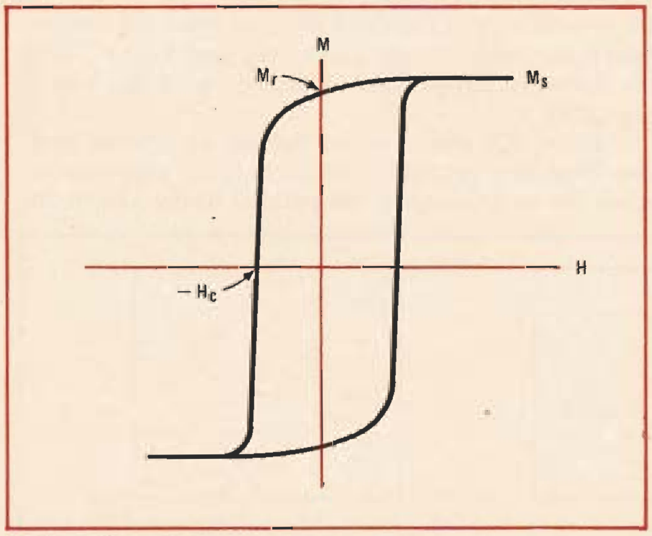
As the magnetic field is increased the magnetization



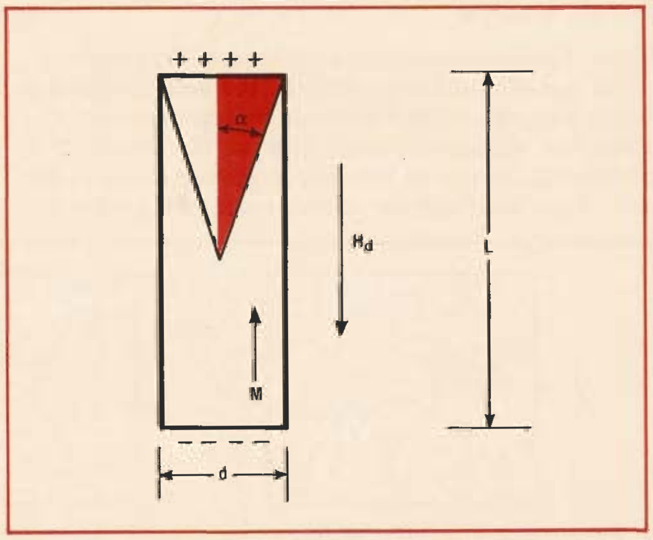
2. Magnetic boundaries. A typical magnetization process occurs in three phases: first, a reversible phase in which the domain boundaries move, next an irreversible phase, and finally the domain walls in effect disappear with all the magnetization in one direction.



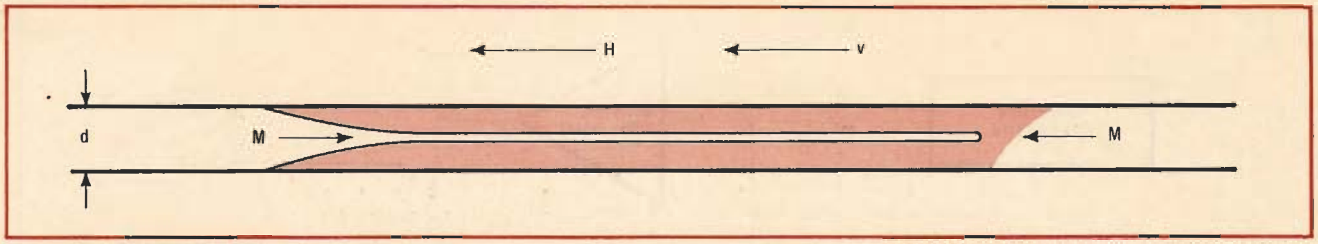
4. Poles apart. Magnetic poles, formed on the uniformly magnetized surfaces of a cylinder, establish a magnetic field opposite to the direction of the magnetization. If the external field is removed, the field established by the poles tends to demagnetize the sample.



3. Magnetic switch. In this plot of a typical hysteresis curve, the coercive field H_c is the reverse field necessary to bring the magnetization M to zero; the remanence M_r is the value of M at H = O; and the saturation magnetization M_s is the limiting value of M.



5. In reverse. The demagnetization field of a long cylinder (wire) will be proportional to d/L. This demagnetization field operates in a saturated material when the external magnetization field is removed, which is a key factor in the Wiegand effect.



6. Wire domain. The approximate shape of the domain formed during the switching process in an inelastically stretched nickel-iron wire travels down the wire at a rate of about 2 × 10^5 centimeters per second. At this velocity, switching times are on the order of 100 μs.

enters a "set" or magnetized condition when the cylindrical domain wall between the shell and the core in effect disappears. On reduction of the magnetic field, the core reverses direction again, producing a cylindrical domain wall at the "reset" value of the field. The treated short wire, therefore, produces the magnetic loop (Fig. 7) that can be applied to various product designs.

In the Wiegand-effect devices, the wire is made of a variety of magnetic alloys. Two readily-available materials include Permalloy (50 Ni, 50 Fe) and Vicalloy (10 V, 52 Co, 38 Fe). By a twisting action, the shell of a 10-mil wire is work-hardened to produce a coercive field of 20 to 40 Oe. The core meanwhile maintains a relatively low coercive field, in the neighborhood of 5 Oe. Thus, in a long wire saturated to the right, the core switches in an applied field of about ±5 Oe to either the left or the right with the magnetization of the shell remaining unchanged.

If the ratio of length to diameter is chosen properly, the demagnetization field of the wire will be large enough for the set and the reset processes to occur for magnetic fields over the range of 0 to 20 oersteds.

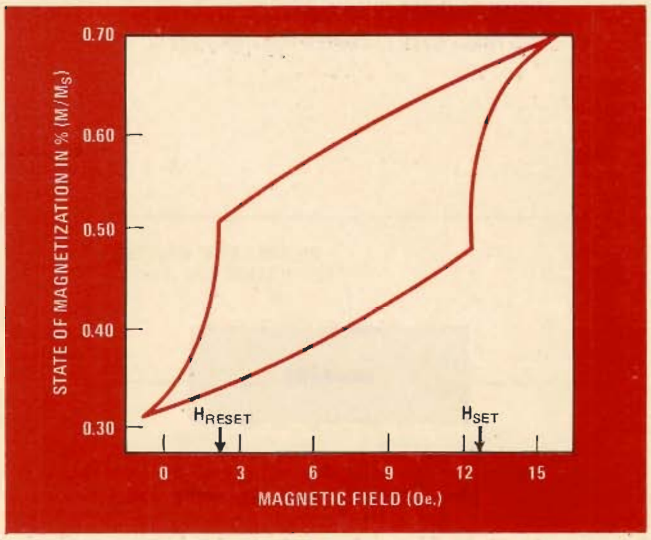
As for the short-wire configuration, the demagnetization will be given by $H_D = -c(d/L)\overline{M}$. The value of c will depend on the degree of magnetic saturation, and will probably be less than 4 π. Using the midpoint between H_{set} and H_{reset} as the value of the demagnetization field, the magnitude of c can be determined by computing H_D/M versus d/L for a number of wires, and turns out to be approximately 2 for this case. From the Wiegand loop in Fig. 7, domain wall switching apparently occurs when M/M_s is about 0.5 or when the material is only half saturated. In equation (2), this accounts for the significant deviation of the constant, c, from the expected value of 4 π.

By reversing the applied magnetic field sufficiently to switch the magnetization in the shell, the Wiegand loop will occur in the negative M and H directions, indicating the bipolar nature of the switching process.

Experiments have shown that the velocity of the domain wall in a wire will be given by

$$v = A(H - H_o) \tag{3}$$

where A = 40,000 cm/s Oe for Permalloy and $H - H_o$ is the field acting on the domain wall. In the short wire, H_o is the demagnetization field and H is the applied magnetic field at which the magnetization is reversed. The result is a domain-wall velocity of 2 × 10^5 cm/s. A 1-cm wire should produce a pulse width of 5 microseconds. However, the domain wall observed in Fig. 6 is stretched out to a length of nearly 100 cm. The resulting switching is the creation of a domain wall that propagates from one end to the other in 5 to 10 μs. The domain wall then expands radially at a much lower velocity resulting in a switching time in the neighborhood of 100 μs. The very rapid axial velocity assures one pulse per switch.



7. Wire switch. A key factor in the Wiegand effect is the magnetic loop that provides "set" and "reset" points that are repeatable and depend upon the relative magnetization of shell and core of the wire.

In the switching process, the magnetic system is changing from a higher energy state to a lower energy state. The difference in the energy, Δε, between these states is given by

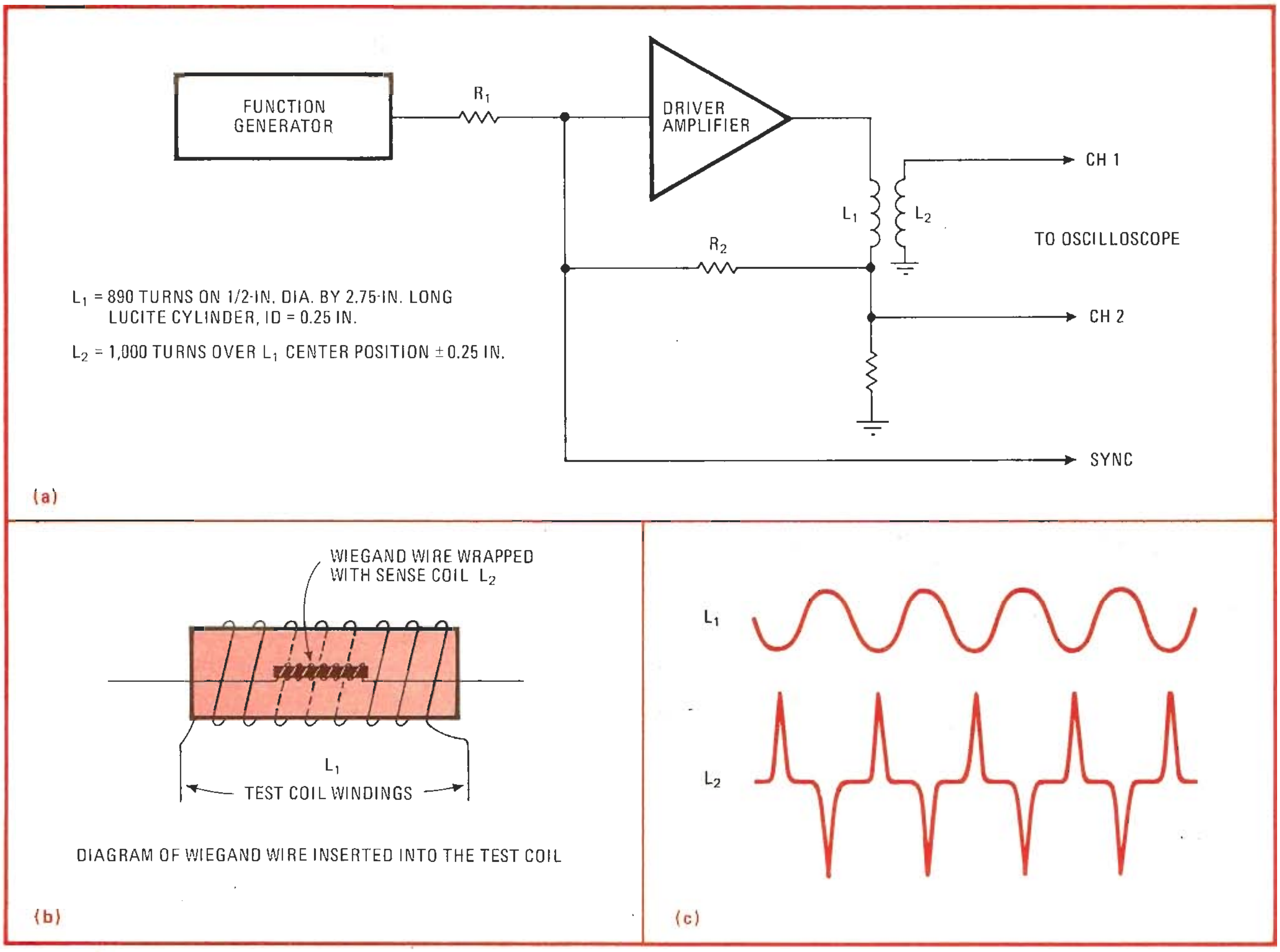
$$\Delta\varepsilon = H_{\text{int}}\,\Delta M V \tag{4}$$

where H_{int} is the internal magnetic field, ΔM is the difference in the magnetization in the two states, and V is the volume of the material involved in the switching process.

Applications

The energy radiated into surrounding space can be detected by appropriately designed detectors. For an internal magnetic field (H_{int}) on the order of 10 Oe, a difference in magnetization before and after switching of 100 gauss (ΔM) and a d/L ratio of 0.01, a 1-cm wire switching in 10^{-4} sec. radiates a power of 2 milliwatts. Experimentally, detector signals up to 500 millivolts have been recorded in 50 ohm loads.

Practical applications of the Wiegand effect are relatively simple to implement. For instance, a magnetic



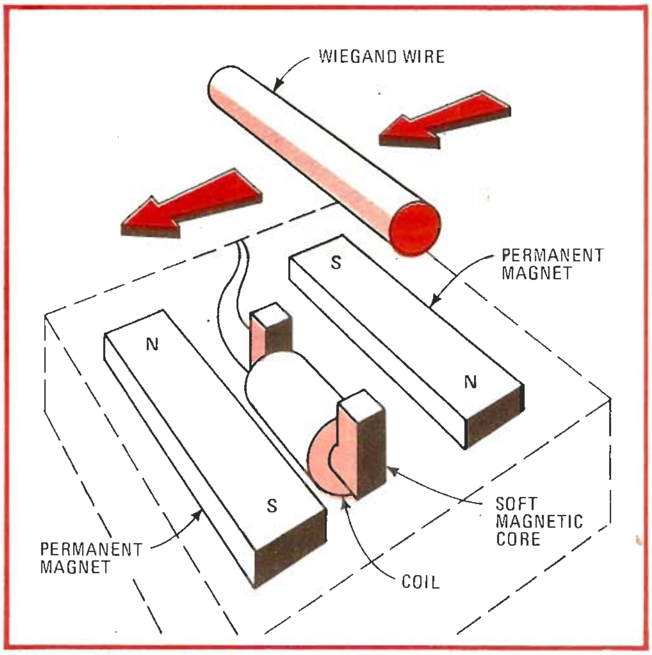
8. Sensing. Typical Wiegand-wire test apparatus (a) has a coil arrangement as in (b). Output signal (c) shows oscilloscope trace of waveforms in drive coil L_1 and sense coil L_2. The means of detecting the signal pulse depends on the particular application, however.

field of 10 oersteds can be applied by a small magnet moving relative to the wire, or by applying a direct current to a coil wrapped around the wire. In either configuration the switching process occurs when the magnetic field achieves a certain magnitude that depends on the length of the wire and the state of the magnetization. The important point is that the switching is independent of the rate at which the magnetic field is applied. The signal in the detector is not rate sensitive, giving the same output for operation at a low or high velocity.

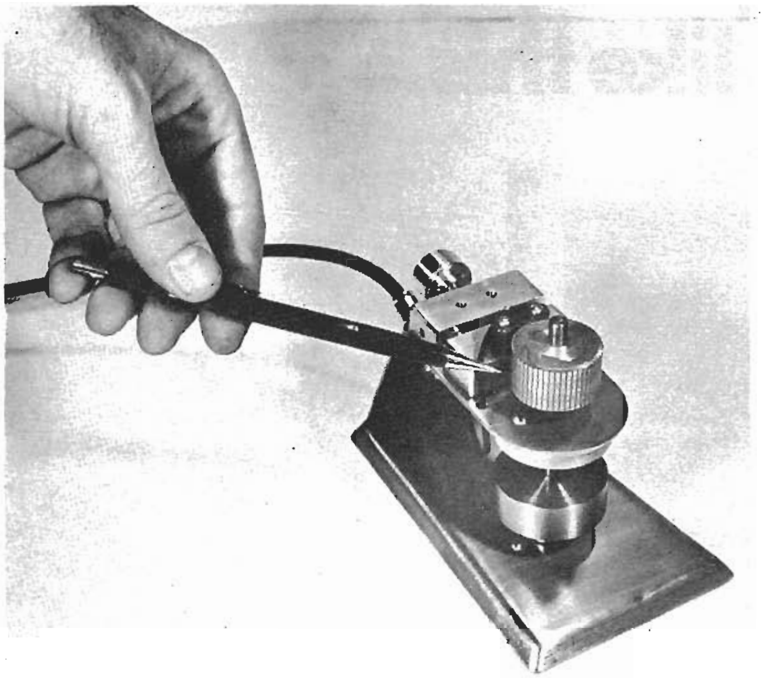
The means of detecting the signal pulse depends on the particular application. If the wire is at rest and the magnetic field in the surrounding space is changing, the detector may be a coil wrapped around the Wiegand wire.

Details of the coil arrangement in a typical test apparatus are down in Fig. 8, where the drive coil is L_1 and the detector or sense coil is L_2. Waveforms of the magnetic field drive in L_1 and the switching signals induced in L_2 are also shown.

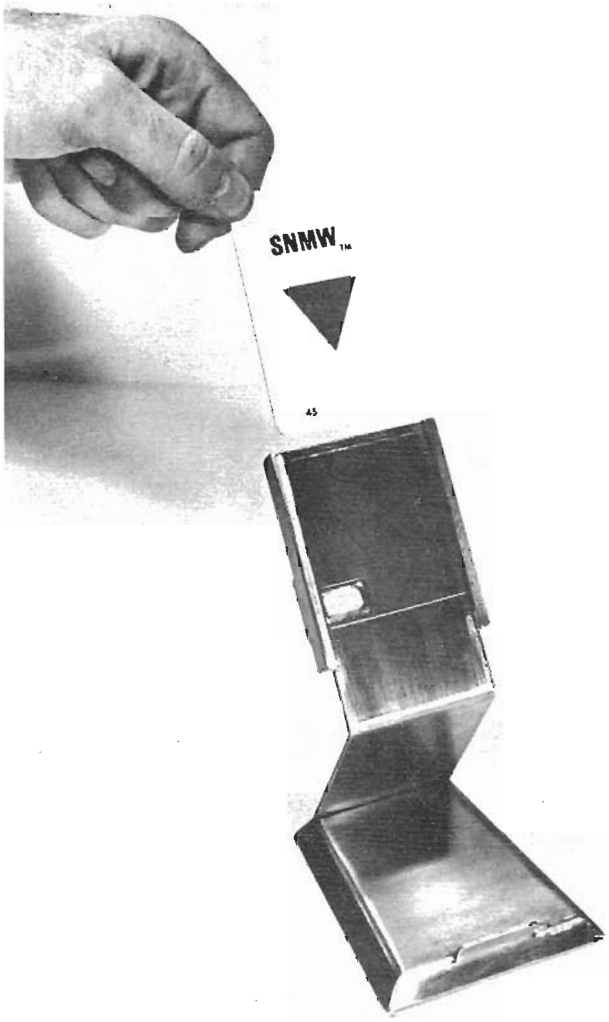
In other applications it is desirable to mount the magnetic wire, or series of wires, on a device moving through a changing magnetic field. A transformer-type read head (Fig. 9) is particularly useful in such an arrangement. A typical system may have up to 150 wires mounted on a 5-cm-diameter wheel. As the wheel ro-



9. Moving on. Schematic of a transformer-style read head shows the "switching" magnets used to control the position of the switching signal for maximum sensitivity of the read head as Wiegand-treated wire passes in direction of the arrow.



10. Turning point. Rotary pulser with Wiegand wires embedded in the rotor could be used for electronic auto ignition since the pulse generated is independent of the velocity of the distributor shaft. As each wire passes the read head a pulse is generated, which could be used to produce, among other things, an ignition spark.



11. Easy reading. As a card reader, a Wiegand-effect system could provide binary-coded signals without need of power line or batteries. Wires in the card slide past the magnetic read head, producing the coded output signal without any other moving parts.

tates, small magnets on the read head cause the switching action (Fig. 10). Such a device requires no electrical input power to the read head, has a signal-to-noise ratio of better than 40 dB, and a uniform signal amplitude at rotation speeds that can vary from near zero to 720 rpm. At a constant angular rotation velocity of the wheel, the reproducibility of the pulse is $\pm 10^{-4}$ seconds or about the width of the pulse. The Wiegand effect is useful in this application because it is a non-contact, solid-state device composed of low-cost stable materials, and has a long lifetime. The output signal varies by less than 2 dB in the temperature range of −50°C to +100°C. It will operate in aqueous, gaseous, organic solvent, or vacuum environment, and if properly encapsulated, it will operate in a corrosive medium.

Because the polarity of the output signal is determined by the form of the external magnetic field, the device can be any combination of direction and polarity to distinguish forward or backward motion. A typical bipolar application of this feature is a plastic card reader using binary coded output signals (Fig. 11). Instead of using the C core shown in Fig. 9, an E core with the coil wrapped on the center leg is used. By properly cancelling the SNMW properties of one half or the other of a Wiegand wire the induced pulse will have either positive or negative polarity.

This type of card reader offers several advantages. The wires cannot be altered or "erased" except by destroying the entire card. The detection system requires no electrical power input to the read head and the detection signal is independent of the velocity of the card as it passes the read head.

The Wiegand-effect device will operate in single-wire or multiple-wire configuration. It also can be used in a wire bundle. In this configuration, the wires switch in a mutually exclusive manner making distinct pulses from each wire detectable. Signals from bundles of four to six wires are readily discriminated, and as many as 20-wire bundles have consistently produced individually-detectable pulses.

By alternating the way wires are arranged, other products have been designed using the same Wiegand-effect technology. A plastic-key cylinder having two or three embedded wires, when pushed into a reader-lock, provides the signal to open a door. Window-mounted Wiegand-effect wires sliding past a simple reader will set off a burglar alarm. The pulse generator described earlier can be designed as an automobile ignition system that will perform at any speed, and in harsh environments. In short, the list of potential products cover many applications that may require a pulse generator or a magnetic-field sensor. □