Problem 1:

(a) How would you engineer a material to have a very small dielectric constant?

To create a small dielectric constant one must eliminate all controllable sources of dipole moments inside the material. Low-$\varepsilon$ materials are typically based on non-polar organic compounds.

(b) How would you engineer a material to have a high dielectric constant under quasistatic conditions?

To achieve a high dielectric constant we need significant internal dipole moments. Typical examples are polar organic molecules and pyroelectric ionic materials (such as ferroelectrics below the Curie point). Both have large, permanent dipole moments.

(c) How would you address the same problem if the dielectric were to be used in a device that operated at a frequency near 1 gigahertz?

A gigahertz is a frequency at the low end of the microwave range. This frequency is a bit high for most polar molecules, since it is difficult for them to reconfigure at this rate, but is essentially quasistatic for most ionic reconfigurations, which proceed at infrared or optical frequencies. We could, therefore, use ferroelectric or pyroelectric materials that have high static dielectric constants.

Problem 2:

(a) To make a glass fiber to transmit information optically, would you select a glass with a relatively high or relatively low index of refraction?

For an optical fiber one would like $\phi_c$ to be as small as possible to minimize light lost at joints, defects, or small ripples on the solid surface. Hence one would use a glass with the highest refractive index that is consistent with other constraints.

(b) The glass fibers that are used for optical transmission of information are chemically doped so that the index of refraction varies from the center to the outside of the cross-section. Why?

Since the fiber has a finite diameter and light spreads spherically from its point of origin, a light pulse that is transmitted down the fiber consists of rays that make various angles to the fiber axis. A ray that propagates at an angle to the axis is reflected off the fiber surfaces, and travels a greater distance per unit length of propagation along the fiber than does a ray that propagates along the fiber axis. In a homogeneous fiber this difference
in path length causes some interference between the rays, with a loss of definition of the light pulse.

To overcome this problem the fiber is chemically doped so that its index of refraction decreases from its axis to its outer diameter. Since the velocity of light increases as the refractive index decreases, rays that are slightly angled to the fiber axis travel faster, and can hence have more nearly the same velocity along the axis of the fiber.

(c) Silica in the form of glass is transparent, while silica in the form of sand is opaque. Why?

Silica (SiO₂) is an insulator with a band gap sufficient to pass visible light, and is hence transparent in bulk form. However, light is always at least partially reflected from an interface at which the index of refraction changes. If the silica is crushed into a sand of fine particles, reflection from the surfaces of the sand particles scatters incident light so that it cannot penetrate. (If you examine a sample of fine sand in a low-power microscope you will observe that the individual sand particles are transparent, as are cubes of table salt.)

Problem 3:

An n-p-n junction in a photoconductor can be made to behave as a photonic transistor that resembles a MOSFET in its electrical characteristics. Let a voltage difference be imposed between the source and drain. In the absence of illumination the current is very small. However, the current increases dramatically if the device is illuminated with appropriate light. Explain this behavior.

The dominant characteristic of a MOSFET is that it is a tunable switch. When a voltage difference is imposed across the n-p-n junction it has a low conductivity because one of the p-n junctions, that between the gate and drain, is in reverse bias. Hence the current is low; the switch is off. If a sufficiently large positive voltage is applied to the gate its electrical character inverts from n-type to p-type. The electron conductivity of the gate becomes substantial, and an appreciable current can pass between source and drain. The switch is on. Under equilibrium conditions the conductivity of the gate increases strongly with the magnitude of the voltage imposed on it. Hence the switch is tunable; the current for a given voltage between source and drain can be controlled by adjusting the imposed voltage on the gate.

Now consider an n-p-n junction in which the gate is a photoconductor. When the gate is not illuminated, the device behaves like a MOSFET in the off state. However, illuminating the gate with a sufficient intensity of sufficiently energetic photons creates a high density of electrons in the conduction band, so that it behaves like a simple resistor and the switch is on. The device current for given voltage between the source and drain increases with the illumination, which controls the steady-state concentration of conduction electrons in the gate; hence the device is tunable by adjusting the intensity of illumination.
Problem 4:

(a) Distinguish between "hard" and "soft" ferromagnets. Which type of material would be preferred for use in an electrical generator? Why?

"Hard" and "soft" ferromagnets are distinguished by the magnetic hysteresis loops or, more conveniently, by their remanent magnetization and coercive force. "Soft" magnetism is easily reversed, "hard" magnets retain most of their magnetization unless forced into reversal. An AC electrical generator reverses its field at 60 cycles/sec (in the US), and will consume a great deal of energy unless the magnetic hysteresis is very small, that is, unless the magnet is "soft".

(b) Suppose you are given a piece of steel that is magnetically "soft" and you wish to make it "hard". How might you do that?

The hysteresis of a ferromagnet is primarily due to the difficulty of moving magnetic domain walls. To "harden" a ferromagnet we add microstructural features such as dislocation or, particularly, non-magnetic precipitates that act to pin domain walls and increase the difficulty of reversing the magnetic field.

(c) For many purposes in electronic devices it is useful to have a material which is simultaneously a ferromagnet and an electrical insulator. However, the magnetic coupling in almost all useful insulating oxides is antiferromagnetic. How can this problem be overcome (as in the ferrites)?

The simplest solution is contained in the behavior of ferromagnetic oxides (the most common are the ferrites), which are insulators that exhibit ferromagnetism even though their magnetic order is antiferromagnetic. These are ionic materials in which the ions that occupy adjacent sites have different magnetic moments. For example, in magnetite (Fe₃O₄) some of the Fe⁺⁺ ions, with a magnetic moment of 4 μₜ, alternate with Fe⁺⁺⁺ ions, whose magnetic moment is 5μₜ. Even though the core moments align in opposite directions there is a net magnetic moment because of the difference in the magnitude of the magnetic moments of the adjacent ions.

The principal use of the ferrites is in electronic devices in which the direction of the magnetic field is switched at high frequency. Since a changing magnetic field induces an electric current, by Maxwell's equations, "eddy" currents appear in a metallic ferromagnet whose field direction is cycled, and energy is lost. Since the ferrites are insulators, eddy currents and their corresponding energy losses are minimized.

Problem 5:

(a) Type I and a type II superconductors are distinguished by their behavior in magnetic fields. Describe the difference and the qualitatively different mechanism by which a magnetic field penetrates into a type II superconductor.

A type II superconductor is one in which the "coherence length", the effective separation between electrons in a Cooper pair, is less than the "penetration depth", the depth
to which a magnetic field penetrates into the superconductor. When this is the case it is possible for the magnetic flux to penetrate into the material in the form of discrete filaments or "flux vortices" of normal material without forcing the whole superconductor to become normal. Since the partial penetration of the magnetic field in the form of flux vortices relieves much of the thermodynamic driving force for field penetration (and, hence, loss of superconductivity), it is possible for a type II superconductor to remain superconducting to much higher field ($H_{c2}$) than a type I conductor.

(b) One of the principal applications of superconductors is in high-field magnets. The superconductors used for this purpose are type II. Why?

Along with the high critical field of a type II superconductor comes the ability to carry high currents (high critical current). The association is due to the fact that high current produces a high field which will quench the superconductor unless the critical field ($H_{c2}$) is very high.

(c) The critical current of a type II superconductor tends to increase as the material is made "dirtier" by introducing lattice defects. Why?

There is a second mechanism of quenching superconductivity in a type II superconductor which is, in fact, the usual mechanism that limits the critical current. The Lorenz force that connects the current and the magnetic field has the consequence that the current will set the magnetic flux lines into motion unless they are constrained. The motion of the flux lines liberates energy (work is done on them) which heats the material and causes it to lose superconductivity. It follows that the critical current increases as the flux lines become more strongly pinned against motion. Lattice defects such as grain boundaries and precipitates are used to accomplish this.