光机电系统概论

Introduction to Opto-mechatronics Systems

刘双峰 王 高 编著

北京理工大学出版社
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前　　言

光机电技术是面向应用的跨学科的技术，它是光信息技术、机械技术、微电子技术、信息技术和控制技术、通信技术等有机融合的一门综合性学科。

为方便光学与光电技术及仪器、激光加工技术、先进制造技术、通信工程等相关专业技术人员查阅外文资料，了解更多国外的前沿科技动态，编者根据多年的教学实践，将一些相关的基础知识进行了总结，编写成此书。

全书共分 12 个单元。第 1 单元主要介绍机械传感器；第 2 单元主要介绍光发射器；第 3 单元主要介绍基本的光纤器件；第 4 单元主要讨论放大器；第 5 单元主要介绍脉冲雷达；第 6 单元主要介绍通信系统中的计算机仿真设计和分析；第 7、第 8、第 9 单元主要介绍可视探测器、红外探测器及图像探测器；第 10 单元是机械工程的总体介绍；第 11 单元为一个轴的设计过程；第 12 单元为螺杆压缩机的优化设计。

本书由中北大学刘双峰、王高合编，由于水平有限，错误及不足之处在所难免，诚望广大读者批评指正。

编　者

Contents

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Mechanical Sensor

There is a tremendous variety of direct mechanical sensors that have and could be micromachined. In order to study this vast area, it makes sense to begin with a discussion of the basic mechanical sensing mechanisms (e.g., for force, displacement, strain, etc.) and then see how these mechanisms can be applied to realize a wide range of micromachined sensors.

The following table 1-1 summarizes the commonly used mechanical sensing mechanisms in micromachined devices. Important considerations when choosing such a mechanism include the need for local circuitry, whether or not the transduction mechanism is DC-responding, temperature coefficients, long-term drift, overall system complexity, and others.

Table 1-1 Comparison of some major properties of the mechanical sensing mechanisms commonly used in micromachined devices

Mechanism	Parameter Sensed	Local Circuits	DC Response	Complex System	Linearity	Issues
Metal Strain Sensor	strain	NO	YES	+	+++	• low sensitivity • very simple
Piezoresistive Strain Sensor	strain	NO	YES	+	+++	• temperature effects can be significant • easy to integrate
Piezoelectric	force	NO	NO	++	++	• high sensitivity • fabrication can be complex
Capacitive	displacement	YES	YES	++	poor	• very simple • extremely low temperature coefficients
Tunneling	displacement	YES	YES	+++	poor	• sensitive to surface states •drift performance not yet proven
Optical	displacement	NO	YES	+++	+++	• rarely employed in mechanical microsensors

1.1 Resistive and Piezoresistive Strain Sensor

Strain sensors are an integral part of many micromachined devices, serving to measure strain or, indirectly, displacement of structures. A strain gauge is a conductor or semiconductor that is fabricated on or bonded directly to the surface to be measured. Changes in gauge dimensions result in proportional changes in resistance in the sensor. This is partly due to stretching (changes in dimension) and partly due to the piezoresistive effect. As might be expected, the sensitivity of gauges can be quite different, depending on their design. Strain gauges of all types can be very linear over considerable ranges of strain, making them attractive in a variety of applications.

In general, the sensitivity is expressed by the gauge factor (dimensionless),

$$GF = \text{relative resistance change/strain} = \left(\Delta R/R\right)/\left(\Delta L/L\right) = \Delta R/\varepsilon_1 R \qquad (1\text{-}1)$$

One can use partial derivatives to derive a general expression for the gauge factor in terms of the physical parameters of the strain gauge. This begins with the derivation of a relation between resistance and changes in its underlying parameters, as seen in,

$$R=\rho L/A, \text{ in } \Omega \qquad (1\text{-}2)$$

where,

ρ = resistivity, in Ω • cm;

L = length, in cm;

A = cross-sectional area, in cm^2.

Differentiating the resistance equation, one obtains,

$$\mathrm{d}R = \frac{\rho}{A}\mathrm{d}L + \frac{L}{A}\mathrm{d}\rho - \frac{\rho L}{A^2}\mathrm{d}A \qquad (1\text{-}3)$$

which can be divided by the above equation for resistance to obtain,

$$\frac{\mathrm{d}R}{R} = \frac{\mathrm{d}L}{L} + \frac{\mathrm{d}\rho}{\rho} - \frac{\mathrm{d}A}{A} \qquad (1\text{-}4)$$

It must be noted that from this point in the derivation it becomes geometry-specific, and a cylindrical wire is assumed for simplicity. It is useful to use Poisson's ratio to express the relative dimensional change in diameter, D, versus length, L,

$$\nu = -\frac{\varepsilon_t}{\varepsilon_1} = -\frac{\frac{\Delta D}{D}}{\frac{\Delta L}{L}} \approx -\frac{\frac{\mathrm{d}D}{D}}{\frac{\mathrm{d}L}{L}} \qquad (1\text{-}5)$$

where, for a cylinder, the area and diameter are related through,

$$A = \frac{\pi D^2}{4} \text{ and } \frac{\mathrm{d}A}{A} = \frac{2\mathrm{d}D}{D} \qquad (1\text{-}6)$$

which in turn allows Poisson's ratio to be written and rearranged to obtain,

$$\frac{\mathrm{d}A}{A} = -2\nu\frac{\mathrm{d}L}{L} \qquad (1\text{-}7)$$

finally allowing the differential form of the resistance to be written,

$$\frac{dR}{R} = (1+2\nu)\frac{dL}{L} + \frac{d\rho}{\rho} \tag{1-8}$$

where the first term represents the dimensional effect and the second term represents the piezoresistive effect (change in resistivity of the material of the strain gauge). From this, the gauge factor can be expressed in terms of these parameters as,

$$GF = \frac{\frac{dR}{R}}{\frac{dL}{L}} = \frac{\frac{dR}{R}}{\varepsilon_1} = (1+2\nu) + \frac{\frac{d\rho}{\rho}}{\varepsilon_1} \tag{1-9}$$

Naturally, such a derivation can be carried out for strain gauges with non-cylindrical shapes.

As shown in table 1-2, the gauge factors of different types of strain gauges can be vastly different, due mainly to whether or not they have a significant piezoresistive effect (as do the semiconductor types).

Table 1-2 Comparison of the gauge factors of different types of strain gauges.

Type of Strain Gauge	Gauge Factor
Metal Foil	1 to 5
Thin-Film Metal	≈2
Bar Semiconductor	80 to 150
Diffused Semiconductor	80 to 200

1.1.1 Metallic Strain Gauges

For metals, ρ does no vary significantly with strain (as long as the cross-sectional dimensions are much larger than the grain size), and ν is typically in the range of 0.3 to 0.5, for gauge factors on the order of two. However, in practice, macroscopic metal strain gauges often have gauge factors higher than this, so it appears that some piezoresistive effect and/or change in total wire volume comes into play. Whether or not this would be helpful in micromachined strain gauges is most likely a moot point since the much larger gauge factors of piezoresistive strain gauges make them nearly ubiquitous in this domain. (Figure 1-1)

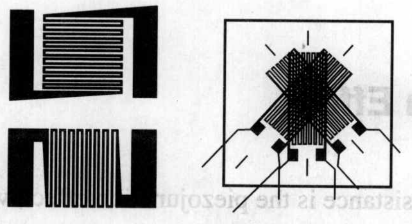

Figure 1-1 Illustration of typical metal strain designs

Metal strain gauges may be made from thin wires or metal films (thin-film strain gauges) that may be directly fabricated on top of microstructures. Thin-film metal strain gauges are easier to fabricate (photolithographically) and allow for more complex shapes. They are generally built on flexible plastic substrates (sometimes self-adhesive) and can be glued onto a surface.

1.1.2 Semiconductor Strain Gauges

In semiconductor strain gauges, the piezoresistive effect is very large, leading to much higher gauge factors. P-type silicon has gauge factor up to 200 and n-type has a negative gauge factor, down to ≈ -140. Stain gauges can be locally fabricated in bulk silicon through ion implantation or diffusion, or the entire substrate can be used as the sensor. Unfortunately, these semiconductor strain gauges also have much higher-temperature coefficients of resistivity, making temperature compensation more important. (For example, one can use a Wheatstone bridge with a reference strain gauge that is not deformed to compensate, as long as all bridge elements are isothermal.)

The detailed theory of piezoresistivity is not covered herein. In short, the effective mobilities of majority carriers in a piezoresistive material are affected by stress (this effect is highly orientation dependent). For p-type materials, the effective mobility of holes decreases so the resistivity increases. For n-type materials, the effective mobility of electrons increases so the resistivity decreases. The observed change in mobility results from the strain-induced distortions of the energy band structure, and this can be calculated quite accurately if necessary.

While the strong temperature dependence of the gauge factor for single-crystal semiconductor strain gauges makes their use sometimes more difficult, polycrystalline and amorphous silicon are useful alternatives (which are not anisotropic). The total resistance of polycrystalline silicon is determined by the resistance of the silicon grains and that of the grain boundaries, the latter being the most important aspect. Within the grains, the resistivety behaves essentially like that of the single-crystal material, and so as the temperature increases, the mobility decreases and the resistivety increases. At grain boundaries, depletion regions develop due to charge trapping, and here as the temperature increases, more carriers can overcome these boundaries, decreasing the resistivety. By balancing these effects, the net temperature coefficient can be adjusted to nearly zero. It is worth pointing out that silicon (and polysilicon and amorphous silicon) are centrosymmetric and not piezoelectric (unless stressed). Piezoresistive behavior is completely different from piezoelectric properties.

1.2 Piezojunction Effect

A related effect to piezoresistance is the piezojunction effect, which is a marked shift in the I-V characteristic of p-n junction when mechanical stresses are applied to it. One can also fabricate pressure sensitive tunnel diodes, MOSFETs, MESFETs, etc. While this effect has been discussed in the micromachining literature, little use has been made of it in micromachined transducers. Friedrich, et al. (1997) presented a piezojunction-based strain sensor where reverse I-V characteristics, dominated by band-to-band tunneling, were modulated by applied strain.

1.3 Piezoelectric Effect

Piezoelectricity is a phenomenon in which a mechanical stress on a material produces an electrical polarization and, reciprocally, an applied electric field produces a mechanical strain (Figure 1-2). The Curies discovered the effect in 1800, and the first useful applications were made by Cady in 1921 with his work on quartz resonators. The effect can certainly be used to sense mechanical stress and as an actuation mechanism. However, a key potential limitation of this transduction mechanism is that the piezoelectric effect produces a DC charge (polarization), but not a DC current. Thus such transducers are inherently incapable of providing a DC response. The limited low-frequency response of piezoelectric devices is primarily due to parasitic charge leakage paths, and can be significantly improved through micromachining and directly coupling piezoelectric outputs to MOSFET gates.

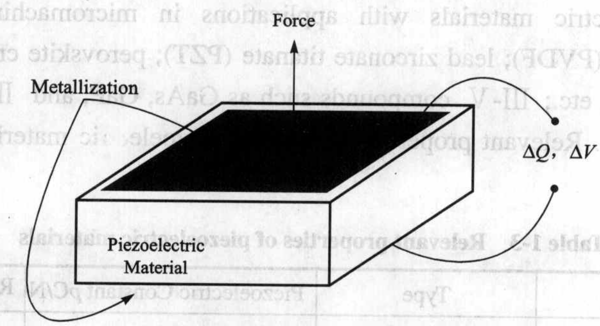

Figure 1-2 Generation of incremental charge on metallized electrodes

Centrosymmetric crystals such as silicon and germanium are not piezoelectric. If such materials are strained, the effective centers of the positive and negative charges do not move with respect to each other, preventing the formation of dipoles as required for piezoelectricity. Thus, materials whose crystal structures lack centers of symmetry are required for the piezoelectric effect to be possible. Thus, to fabricate silicon-based piezoelectric transducers, a suitable material must to be deposited on the devices. The III-V and II-VI compounds (e.g., GaAs, CdS, ZnO, etc.) are not centrosymmetric and have bonds that are partly covalent and partly ionic in nature, and thus are piezoelectric. Materials such as CdS and ZnO can be deposited by co-evaporation or sputtering, with the sputtered ZnO being more common approach.

Piezoelectricity, pyroelectricity, and ferroelectricity all derive from one single physical cause: the existence of an electric polarization vector, *P*. As a rule of thumb, if a crystal is piezoelectric, almost always it will be pyroelectric and ferroelectric too. This points out another factor which limiting the use of piezoelectric sensing for low frequencies and DC, since most suitable materials exhibit considerable temperature errors due to their pyroelectric behavior. This effect can, however, be mitigated through the use of compensation capacitors made from the same piezoelectric material but left strained.

In terms of sensitivity to stress, piezoelectric materials are commonly characterized by the charge sensitivity coefficients, d_{ij}, (in units of C/N), which relates the amount of charge generated at the surfaces of the material (of area A) on the i axis the applied force, F, on the j axis,

$$\Delta Q_i = d_{ij}\Delta F_j = d_{ij}\Delta\sigma A \tag{1-10}$$

From this, the voltage change across the conductive plates (at a spacing x) can be written as,

$$V = \frac{Q}{C} = \frac{Qx}{\varepsilon_0\varepsilon_r A} \rightarrow \Delta V_i = \frac{d_{ij}\Delta F_j x}{\varepsilon_0\varepsilon_r A} \tag{1-11}$$

The piezoelectric effect is reversible, such that the application of a voltage ΔV gives rise to a corresponding force, ΔF, and resulting dimensional change ΔL. This is commonly used in piezoelectric actuators. Typical values for ΔL vary between 10^{-10} and 10^{-7} cm/V. Thus, to obtain displacements on the order of micrometers (μm), voltages exceeding 1 000 V are often necessary, unless stacked actuators or mechanical motion amplification methods are used.

Common piezoelectric materials with applications in micromachining include quartz; polyvinylidene fluoride (PVDF); lead zirconate titanate (PZT); perovskite crystals such as barium titanate, lithium niobate, etc.; Ⅲ-Ⅴ compounds such as GaAs, GaP; and Ⅱ-Ⅵ compounds such as ZnO, ZnS, ZnSe, etc. Relevant properties of several piezoelectric materials are given in table 1-3.

Table 1-3 Relevant properties of piezoelectric materials

Material	Type	Piezoelectric Constant pC/N	Relative Permittivity (ε_r)
Quartz	single crystal	d_{33}=2.33[2, 3]	4.5[2], 4.0[3]
Polyvinylidene foride (PVDF)	polymer	d_{31}=20, d_{32}=2, d_{33}=−30[2] d_{31}=23[1] , d_{33}=1.59[3]	12[1, 2]
Barium titanat ($BaTiO_3$)	ceramic (Perovskite crystal)	d_{31}=78[1, 2] d_{33}=190[3]	1 700[1, 2] 4 100[3]
Lead zirconate titanate (PZT)	ceramic	d_{31}=110[1, 2] d_{33}=370[3]	1 200[1] 300 to 3 000[3]
Zinc oxide (ZnO)	metal oxide	d_{33}=246[4]	1 400[4]

PZT is a ceramic with a high value for the piezoelectric strain constant. However, it is somewhat difficult to deposit as a thin film. Polyvinylidene fluoride (PVDF) and ZnO are most often used in the microfabrication of piezoelectric transducers.

PVDF, which is a carbon-based polymer, is usually deposited as a spin cast film from a dilute solution in which PVDF powder has been dissolved. As for most piezoelectric materials, processing after deposition greatly affects the behavior of the PVDF film. For example, heating and stretching can increase or decrease the piezoelectric effect. PVDF and most other piezoelectric films require a polarization after deposition. This is done by the application of a large electric field for a few hours using electrodes deposited on both sides of the film. The net polarization at the end of this process depends on the time integral of the applied field up to a saturation level.

ZnO is the most common piezoelectric material used in micro fabrication. Unlike PVDF, it can be sputter-deposited as a polycrystalline thin film with its c-axis (along which piezoelectricity is strongest) perpendicular to the surface of the substrate. Pure Zn is usually sputtered in an O_2/Ar plasma to form ZnO. ZnO has also found broad application as a pyroelectric material.

Piezoelectric actuation is ideal, however, for scanning tunneling and scanning force microscopes, where small, precise displacements are required. Piezoelectric materials are also very useful in micromachined transducers such as surface acoustic wave (SAW) devices, accelerometers, microphones, etc.

1.4 Capacitive Sensing

Perhaps one of the most important, and oldest, precision sensing mechanisms is capacitive. The physical structures of capacitive displacement sensors are extremely simple (one or more fixed plates, with one or more moving plates). The inherent nonlinearity of most capacitive sensors is often overshadowed by their simplicity and very small temperature coefficients. With the monolithic integration of signal conditioning circuitry, the additional problem of measuring often miniscule capacitance changes in the face of large parasitics is mitigated. Several potential capacitive sensing modes are illustrated in Figure 1-3.

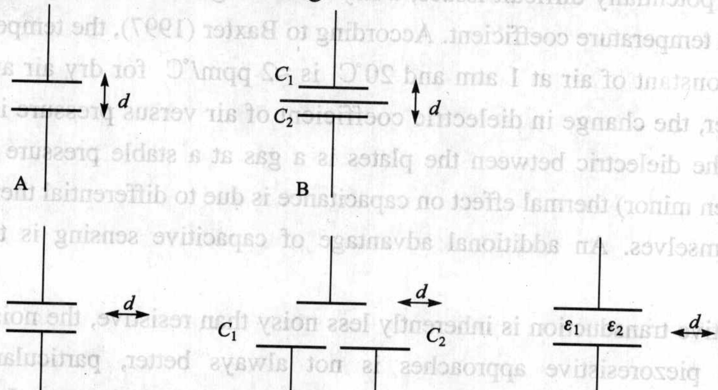

Figure 1-3 Five different possible capactive sensing modes

The basic parallel-plate capacitor equation is,

$$C = \varepsilon_0 \varepsilon_r A/d \text{, in F} \tag{1-12}$$

where,

ε_0 = dielectric constant of free space = 8.854 188×10^{-14} F/cm;

ε_r = relative dielectric constant of material between the plates;

A = overlapping plate area, in cm;

d = plate separation, in cm.

Similarly, as is often the case in miromachined structures, for n dielectric layers of a relative dielectric constant, ε_{ri} , the overall capacitance is,

$$C = \frac{\varepsilon_0 A}{\left(\frac{d_1}{\varepsilon_{r1}} + \frac{d_2}{\varepsilon_{r2}} \cdots + \frac{d_n}{\varepsilon_{rn}}\right)}, \text{ in F} \tag{1-13}$$

Capacitive sensor structures are relatively simple to fabricate. As illustrated above, one can vary d, ε, or A , providing very nonlinear (in the former two cases) or quite linear position-to-capacitance transfer functions (in the latter case). While macroscopic capacitive transducers of nearly any imaginable shape can be implemented, this is not the case for micromachined devices. Membrane-type capacitive devices (e.g., microphones or pressure sensors) are straightforward to fabricate, but they are extremely nonlinear, since d varies. Comb type capacitors are commonly used in surface micromachined devices, and are theoretically based on varying the overlapping area for greater linearity. However, at such scales (particularly for surface micromachined devices), fringing fields can become very significant or even dominant. Thus, the parallel-plate capacitor equation is only useful for first-order estimates at best. Varying the dielectric constant between the plates appears not to have been employed in micromachined devices often, and there seems to be little incentive to do so given the relative ease of using the other two modes. One noteworthy exception is the class of humidity and chemical sensors in which the dielectric constant of a sensitive layer is varied in relation to the concentration of analyte.

Despite these potentially difficult issues, a key redeeming feature of capacitive transducers is their near lack of a temperature coefficient. According to Baxter (1997), the temperature coefficient of the dielectric constant of air at 1 atm and 20℃ is ≈2 ppm/℃ for dry air and 7 ppm/℃ for moist air. However, the change in dielectric coefficient of air versus pressure is more sizable at 100 ppm/atm. If the dielectric between the plates is a gas at a stable pressure (or vacuum), the dominant (and often minor) thermal effect on capacitance is due to differential thermal expansion of the structures themselves. An additional advantage of capacitive sensing is the fact that it is non-contact.

While capacitive transduction is inherently less noisy than resistive, the noise performance of capacitive versus piezoresistive approaches is not always better, particularly since surface micromachining approaches often result in extremely small capacitances. In such cases, the necessary electronics often supplies enough noise to eliminate any potential signal-to-noise ratio (SNR) advantage of capacitive sensing.

Changing capacitance can be measured using a number of well-known circuit techniques, such as (1) charge-sensitive amplifiers, (2) charge-redistribution techniques, (3) impedance measurements,

(4) RC oscillators, and (5) direct charge coupling.

In general, these circuits can be integrated with the capacitive sensors themselves, or at least positioned nearby to minimize the effects of parasitic capacitances.

Such electrostatic devices are also capable of being used as actuators, but are very nonlinear in this mode.

1.5 Tunneling Sensing

Tunneling transduction is extremely sensitive due to the exponential relationship of tunneling current, I, to the tip/surface separation,

$$I = I_0 e^{(-\beta\sqrt{\phi}z)} \tag{1-14}$$

where,

I_0 = scaling factor, dependent on materials, tip shape, etc.;

β = conversion factor, typical value = 10.25 $eV^{-1/2}$/nm;

ϕ = tunnel barrier height in electron-volts (eV), typical value = 0.5 eV;

Z = tip/surface separation in nanometers (nm), typical value = 1 nm.

While extremely nonlinear, the sensitivity of this displacement sensing approach can be harnessed by using closed-loop feedback to linearize the system. Also, while imaging microscopy applications call for extremely (atomically) sharp tunneling tips, this is not necessary displacement sensing applications since one atom or another will be closest to the tunneling current sink and will thus dominate. To date, there have been limited applications of tunneling transduction in micromachined systems.

Question

What is the simplest sensor?

Words and Expressions

1. amorphous *adj.* 无定形的，无组织的
2. analyte *n.* （被）分析物
3. anisotropic *adj.* 各向异性的
4. barium titanate 钛酸钡
5. bulk *adj.* 大批的，大量的（在体积、数量或容积上大的）
6. centrosymmetric *adj.* 中心对称的
7. ceramic *adj.* 陶瓷［质］的
8. compound *n.* 混合物，［化］化合物
9. covalent *adj.* 共价的
10. cross-section *n.* 横截（断）面
11. cylindrical *adj.* ［计］圆柱的
12. deformed *adj.* 变形的，形状上被扭曲的，畸形的

13. depletion *n.* 损耗
14. derivative *adj.* 引出的，系出的
n. 派生的事物，派生词
15. derive *vt.* 得自
vi. 起源
16. dielectric *n.* 电介质，绝缘体
adj. 非传导性的
17. differentiating *vt.* ［数学］求……的微分，计算导数或（函数的）微分
18. dilute *vt.* 冲淡，稀释
adj. 稀释的
19. dimensionless *adj.* 无量纲的，无因次的
20. dipoles *n.* 双极子，偶极
21. distortion *n.* 扭曲，变形，曲解，失真
22. dominant *adj.* 有统治权的，占优势的，支配的
23. ferroelectricity *n.* 铁电现象
24. foe *n.* 反对者，敌人，危害物
25. foil *n.* 箔，金属薄片，［建］叶形片，烘托，衬托
vt. 衬托，阻止，挡开，挫败，贴箔于
26. fringing *n.* 边缘现象，散射现象
27. gauge *n.* 标准尺，规格，量规，量表
v. 测量
28. germanium *n.* 锗
29. herein *adv.* 于此，在这里
30. humidity *n.* 湿气，潮湿，湿度〈美〉，沼泽中的肥沃高地
31. impedance *n.* ［电］阻抗，全电阻，［物］阻抗
32. implantation *n.* 培植，灌输
33. incentive *n.* 动机
adj. 激励的
34. induce *vt.* 劝诱，促使，导致，引起，感应
35. inherently *adv.* 天性地，固有地
36. ion *n.* 离子
37. isothermal *adj.* 等温的，等温线的
n. 等温线
38. linearize *vt.* 使线性化
39. lithium *n.* ［化］锂
40. longitudinal *adj.* 经度的，纵向的
41. macroscopic *adj.* 肉眼可见的，巨观的
42. mechanism *n.* 机械装置，机构，机制
43. membrane *n.* 膜，隔膜
44. MESFET *abbr.* Metal Semiconductor Field Effect Transistor 的缩写，金属半导体场效应晶体管
45. microscopy *n.* 显微镜方法
46. miniscule *adj.* 极小的，细微的
47. monolithic *n.* 单片电路，单块集成电路
48. moot *adj.* 未决议的，无实际意义的
49. MOSFET *abbr.* Metal Oxide Semiconductor Field Effect Transistor 的缩写，金属氧化物半导体场效应管
50. niobate *n.* 铌酸盐
51. noteworthy *adj.* 值得注目的，显著的
52. ominated *adj.* 受控的
53. overshadow *vi.* 使显得不重要，遮蔽
54. parasitic *adj.* 寄生的
55. permittivity *n.* 介电常数
56. perovskite *n.* 钙钛矿
57. photolithographic *adj.* 照相平版印刷（法）的
58. piezoelectric *adj.* ［物］压电的
59. piezojunction 压电结
60. plasma *n.* 等离子体，等离子区
61. polarization *n.* 偏振（现象），极化（作用）
62. polycrystalline *adj.* ［物］多晶的
63. polymer *n.* 聚合体
64. polyvinylidene fluoride 聚氟乙烯（PVDF）
65. potential *adj.* 潜在的，可能的，势的，位的
n. 潜能，潜力，电压