
بسم الله الرحمن الرحيم

CHAPTER 1

Energy Bands and Carrier Concentration in Thermal Equilibrium

- In this chapter, we consider some basic properties of semiconductors.
- We begin with a discussion of crystal structure, which is the arrangement of atoms in a solid. We then present the concepts of valence bands and energy bands, which relate to conduction in semiconductors.
- Finally, we discuss the concept of carrier concentration in thermal equilibrium.
- These concepts are used throughout this book.

- Specifically, we cover the following topics:

- Element and compound semiconductors and their basic properties.
- The diamond structure and its related crystal planes.
- The bandgap and its impact on electrical conductivity.
- The intrinsic carrier concentration and its dependence on temperature.
- The Fermi level and its dependence on carrier concentration.

1.1 SEMICONDUCTOR MATERIALS

- Solid-state materials can be grouped into three classes—insulators, semiconductors, and conductors.

- Figure 1 shows the range of electrical conductivities σ (and the corresponding resistivities $\rho = 1/\sigma$)* associated with some important materials in each of the three classes.

*A list of symbols is given in Appendix A.

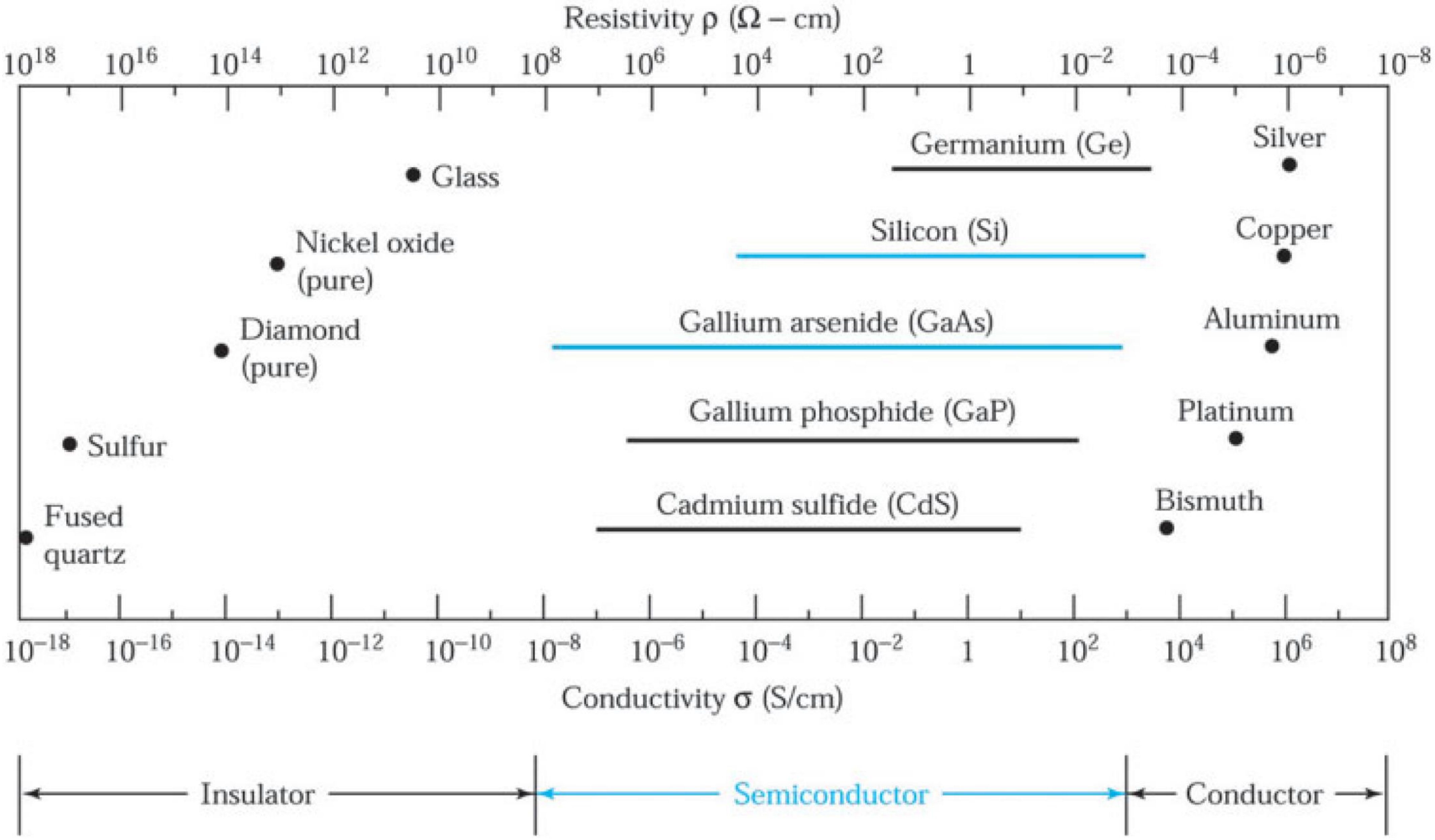

Fig. 1 **Typical range of conductivities for insulators, semiconductors, and conductors.**

- Insulators such as fused(ذوب شده) quartz and glass have very low conductivities, on the order of 10^{-18}– 10^{-8} S/cm; and conductors such as aluminum and silver have high conductivities, typically from 10^{4} to 10^{6} S/cm. §

- Semiconductors have conductivities between those of insulators and those of conductors.

- The conductivity of a semiconductor is generally sensitive to temperature, illumination(تابش نور), magnetic field, and minute amounts(مقدار کمی) of impurity atoms (typically, about 1 μg to 1 g of impurity atoms in 1 kg of semiconductor materials).

§The international system of units is presented in Appendix B.

- This sensitivity in conductivity makes the semiconductor one of the most important materials for electronic applications.

1.1.1 Element Semiconductors

- The study of semiconductor materials began in the early(در اوایل) nineteenth century.
- Over the years many semiconductors have been investigated.
- Table 1 shows a portion of the periodic table related to semiconductors.
- The element semiconductors, those composed of single species of atoms, such as silicon (Si) and germanium (Ge), can be found in Column IV.

TABLE 1 Portion of the Periodic Table Related to Semiconductors

Period	Column II	III	IV	V	VI
2		B Boron	C Carbon	N Nitrogen	O Oxygen
3	Mg Magnesium	Al Aluminum	Si Silicon	P Phosphorus	S Sulfur
4	Zn Zinc	Ga Gallium	Ge Germanium	As Arsenic	Se Selenium
5	Cd Cadmium	In Indium	Sn Tin	Sb Antimony	Te Tellurium
6	Hg Mercury		Pb Lead		

- In the early 1950s, germanium was the major semiconductor material.

- Since the early 1960s silicon has become a practical substitute(جایگزین) and has now virtually(عملا) supplanted(جای چیزی را گرفتن) germanium as a semiconductor material.

- The main reasons we now use silicon are that silicon devices exhibit better properties at room temperature, and high-quality silicon dioxide can be grown thermally. There are also economic considerations.

- Device-grade silicon costs much less than any other semiconductor material.

- Silicon in the form of silica and silicates comprises 25% of the Earth’s crust(پوسته), and silicon is second only to oxygen in abundance.

- Currently, silicon is one of the most studied elements in the periodic table, and silicon technology is by far(تا کنون) the most advanced among all semiconductor technologies.

1.1.2 Compound Semiconductors

- In recent years a number of compound semiconductors have found applications for various devices.
- The important compound semiconductors as well as the two-element-semiconductors are listed in Table 2.
- A binary compound semiconductor is a combination of two elements from the periodic table.
- For example, gallium arsenide (GaAs) is a III-V compound that is a combination of gallium (Ga) from Column III and arsenic (As) from Column V.

TABLE 2 Semiconductor Materials[2]

General Classification	Semiconductor	
	Symbol	Name
Element	Si	Silicon
	Ge	Germanium
Binary compound		
IV-IV ----------------------------	SiC	Silicon carbide
III-V ----------------------------	AlP	Aluminum phosphide
	AlAs	Aluminum arsenide
	AlSb	Aluminum antimonide
	GaN	Gallium nitride
	GaP	Gallium phosphide
	GaAs	Gallium arsenide
	GaSb	Gallium antimonide
	InP	Indium phosphide
	InAs	Indium arsenide
	InSb	Indium antimonide
II-VI ----------------------------	ZnO	Zinc oxide
	ZnS	Zinc sulfide
	ZnSe	Zinc selenide
	ZnTe	Zinc telluride
	CdS	Cadmium sulfide
	CdSe	Cadmium selenide
	CdTe	Cadmium telluride
	HgS	Mercury sulfide
IV-VI ----------------------------	PbS	Lead sulfide
	PbSe	Lead selenide
	PbTe	Lead telluride
Ternary compound	$Al_xGa_{1-x}As$	Aluminum gallium arsenide
	$Al_xIn_{1-x}As$	Aluminum indium arsenide
	$GaAs_{1-x}P_x$	Gallium arsenic phosphide
	$Ga_xIn_{1-x}N$	Gallium indium nitride
	$Ga_xIn_{1-x}As$	Gallium indium arsenide
	$Ga_xIn_{1-x}P$	Gallium indium phosphide
Quaternary compound	$Al_xGa_{1-x}As_ySb_{1-y}$	Aluminum gallium arsenic antimonide
	$Ga_xIn_{1-x}As_{1-y}P_y$	Gallium indium arsenic phosphide

- In addition to binary compounds, ternary compounds and quaternary compounds are made for special applications.

- The alloy semiconductor $Al_xGa_{1-x}As$, which has Al and Ga from Column III and As from Column V is an example of a ternary compound, whereas quaternary compounds of the form $A_xB_{1-x}C_yD_{1-y}$ can be obtained from the combination of many binary and ternary compound semiconductors.

- For example, GaP, InP, InAs, and GaAs can be combined to yield the alloy semiconductor $Ga_xIn_{1-x}As_yP_{1-y}$.

- Compared with the element semiconductors, the preparation of compound semiconductors in single-crystal form usually involves much more complex processes.
- Many of the compound semiconductors have electrical and optical properties that are different from those of silicon.
- These semiconductors, especially GaAs, are used mainly for high-speed electronic and photonic applications.

- Although we do not know as much about the technology of compound semiconductors as we do about that of silicon, advances in silicon technology have also helped progress in compound semiconductor technology.
- In this book we are concerned mainly with device physics and processing technology of silicon and gallium arsenide.
- A detailed discussion of the crystal growth of silicon and gallium arsenide can be found in Chapter 11.

1.2 BASIC CRYSTAL STRUCTURES

- The semiconductor materials we will be studying are single crystals; that is, the atoms are arranged in a threedimensional periodic fashion.
- The periodic arrangement of atoms in a crystal is called a lattice.
- In a crystal, an atom never strays(منحرف شدن) far from a single, fixed position. The thermal vibrations associated with the atom are centered about this position.
- For a given semiconductor, there is a unit cell that is representative of the entire lattice; by repeating the unit cell throughout the crystal, one can generate the entire lattice.

1.2.1 Unit Cell

- A generalized primitive(اوليه) three-dimensional unit cell is shown in Fig. 2.

- The relationship between this cell and the lattice is characterized by three vectors a, b, and c, which need not be perpendicular to each other and may or may not be equal in length.

- Every equivalent lattice point in the three-dimensional crystal can be found using the set

$$\boldsymbol{R} = m\boldsymbol{a} + n\boldsymbol{b} + p\boldsymbol{c}, \qquad (1)$$

where m, n, and p are integers.

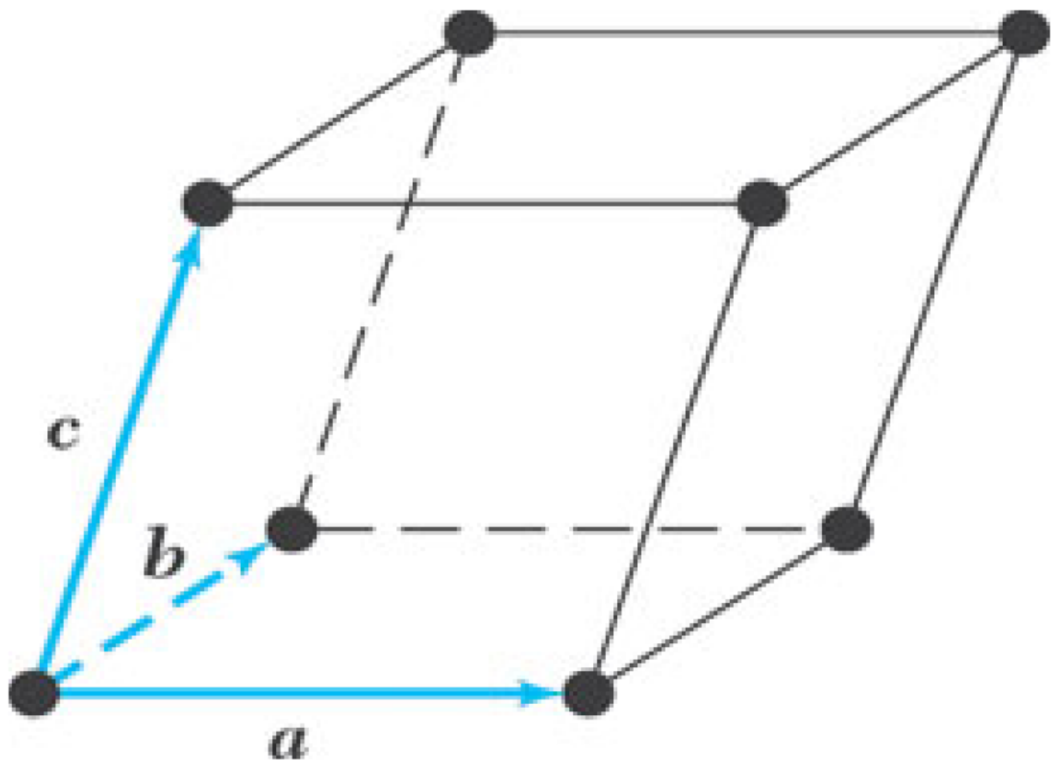

Fig. 2 **A generalized primitive unit cell.**

- Figure 3 shows some basic cubic-crystal unit cells.
- Figure 3a shows a simple cubic (sc) crystal; it has an atom at each corner of the cubic lattice, and each atom has six equidistant nearest-neighbor atoms.
- The dimension a is called the lattice constant.
- In the periodic table, only polonium is crystallized in the simple cubic lattice.
- Figure 3b is a body-centered cubic (bcc) crystal where, in addition to the eight corner atoms, an atom is located at the center of the cube. In a bcc lattice, each atom has eight nearest-neighbor atoms. Crystals exhibiting bcc lattices include those of sodium and tungsten.

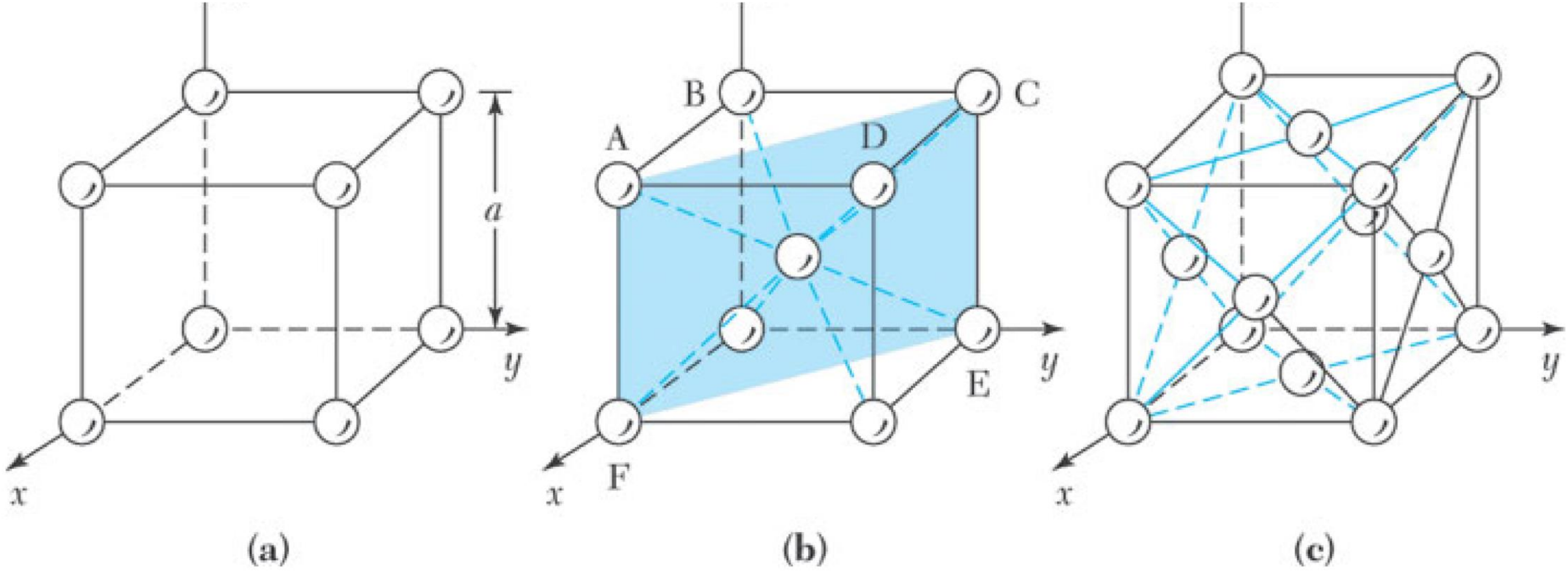

Fig. 3 **Three cubic-crystal unit cells. (*a*) Simple cubic. (*b*) Body-centered cubic. (*c*) Face-centered cubic.**

- Figure 3c shows the face-centered cubic (fcc) crystal that has one atom at each of the six cubic faces in addition to the eight corner atoms. In this case, each atom has 12 nearest-neighbor atoms.
- A large number of elements exhibit the fcc lattice form, including aluminum, copper, gold, and platinum.