My own beliefs are that the road to a scientific discovery is seldom direct, and it does not necessarily require great expertise. In fact, I am convinced that often a newcomer to a field has a great advantage because he is ignorant and does not know all the reasons why a particular experiment should not be attempted.—*Ivan Giaever (discoverer of tunnelling between superconductors), Nobel prize address, 1973*

CHAPTER 10

Superconductivity

10.1 INTRODUCTION

Superconductivity was discovered by H. Kamerlingh Onnes in 1911, three years after his first liquefaction of helium. The availability of this liquid enabled him to investigate the electrical resistance of metals at low temperatues. He chose mercury for study since it could be readily purified by distillation and there was speculation at that time that the resistance of very pure metals might tend to zero at $T = 0$. As can be seen from Fig. 10.1. the observed behaviour was much more dramatic than this; an abrupt transition to a state of apparently zero resistance occurs at a temperature of about 4.2 K. Onnes described the new state as the superconducting state, and it was quickly established that there was no essential connection with high purity; adding substantial amounts of impurity often has little effect on the superconducting transition, although the resistance of the normal state (section 3.3.2) is increased considerably.

Subsequently many metals and alloys have been shown to become superconducting.† The superconducting transition can be very sharp, with a width of less than 10^{-3} K in well annealed single crystals of a metal such as tin. The element with the highest transition temperature, $T_c = 9.2$ K, is niobium (Nb). The search

† Among common metallic elements that *do not* become superconducting at temperatures currently accessible are copper, silver, gold, the alkali metals and magnetically ordered metals such as iron, nickel and cobalt.

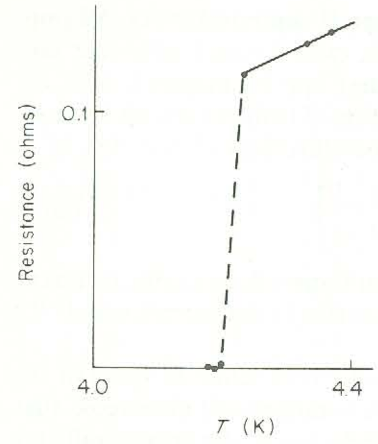

Fig. 10.1 Superconducting transition of mercury. (After H. Kamerlingh Onnes, *Leiden Commun.* **124c** (1911))

for materials with higher transition temperatures led to the investigation of alloys and compounds. In 1972 Nb_3Ge was found to have a T_c of 23 K. For the next 14 years this remained the record T_c and many researchers were misled, with some theoretical justification, into believing that it would not be possible to find materials with significantly higher transition temperatures. In 1986 there was a dramatic breakthrough when Bednorz and Muller found that $La_{2-x}Ba_xCuO_4$ had a T_c of about 35 K for $x \approx 0.15$. This discovery was followed by a frenetic search for other materials. In 1987 $YBa_2Cu_3O_{7-\delta}$ ($\delta \approx 0.1$) was found to have a T_c of 92 K and in 1988 $Bi_2Sr_{3-x}Ca_xCu_2O_{8+\delta}$ ($x \leqslant 1$) raised T_c to 110 K. At the time at which this book was written $Tl_2Ba_2Ca_2Cu_3O_{10}$, also discovered in 1988, has the highest known T_c of 125 K. These new **high-temperature superconductors** are discussed further in section 10.6.

No one has succeeded in measuring a finite resistance to small currents in the superconducting state. The most sensitive method for detecting a small resistance is to look for the decay of a current around a closed superconducting loop. If the resistance of the loop is R and the self-inductance L then the current should decay with time constant $\tau = L/R$. Failure to observe the decay of a **persistent current** has enabled an upper limit of about 10^{-26} Ω m to be put on the resistivity of superconductors as compared to a value of order 10^{-8} Ω m for copper at room temperature (problem 10.1).

10.2 MAGNETIC PROPERTIES OF SUPERCONDUCTORS

10.2.1 Type I superconductors

Superconductors divide into two classes according to their behaviour in a magnetic field. In this section we describe the simpler behaviour of **type I**