Chapter 11
Surface Superconductivity Controlled by Electric Field

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Abstract We discuss an effect of the electrostatic field on superconductivity near the surface. First, we use the microscopic theory of de Gennes to show that the electric field changes the boundary condition for the Ginzburg–Landau function. Second, the effect of the electric field is evaluated in the vicinity of $H_{c3}$, where the boundary condition plays a crucial role. We predict that the field effect on the surface superconductivity leads to a discontinuity of the magnetocapacitance. We estimate that the predicted discontinuity is accessible for experimental tools and materials nowadays. It is shown that the magnitude of this discontinuity can be used to predict the dependence of the critical temperature on the charge carrier density which can be tailored by doping.

11.1 Introduction

The surface of a superconductor is an important region in which the superconductivity nucleates and which represents a natural barrier for penetrating or escaping vortices. It is desirable to control surface properties so that the nucleation can be stimulated or suppressed. An even more attractive task is to open or shut the penetration barrier for vortices. A promising tool of the surface control is the gate voltage for which we can benefit from the extensive technological experience with field effect transistors.

Unfortunately, the interaction of the electric field applied to the metal surface with the superconducting condensate is very weak. Indeed, the superconducting condensate does not interact with the electrostatic potential as shown by Anderson [1]. The condensate feels only the indirect effects like changes of the local density of states or eventual changes of the surface crystal structure.

It is very likely that it will become possible to enhance the field effect on the superconductivity by a proper surface treatment. To this end, it would be of great advantage to understand how the field interacts with the condensate and to have reliable experimental methods directly aiming to measure the strength of this interaction.
To support the experimental effort in this direction, in this chapter, we provide a phenomenological theory of Ginzburg–Landau (GL) type supplemented with the de Gennes boundary condition derived from the microscopic Bardeen, Copper, and Schrieffer (BCS) theory. It will be shown that the boundary condition captures the field effect on the condensate while the GL equation determines how the condensate responds to the field-affected boundary condition.

The field effect on the superconductivity has been measured under various conditions, nevertheless its actual strength is not yet accurately established. The most pronounced field effects are observed on thin layers, in which it is possible to increase or lower their critical temperature [2–6]. These samples are so thin that the applied field considerably changes the total density of electrons, and the observed effect can be interpreted in terms of the modified bulk properties. With thicker samples, one meets the problem that the potential field effect is restricted to the surface, and the underlying bulk overrides its contribution.

At the end of this chapter, we discuss the field effect on the surface superconductivity near the third critical magnetic field $H_{c3}$. In this regime, the bulk superconductivity is absent and the surface superconductivity crucially depends on the boundary condition. We will show that the field effect can be observed via the discontinuity in the magnetocapacitance [7, 8].

### 11.2 Limit of Large Thomas–Fermi Screening Length

To introduce the field effect on the superconductivity, we start from the theory used by Shapiro and Burlachkov [9–14] and by Chen and Yang [15]. It is justified for high-$T_c$ superconductors in which the GL coherence length $\xi$ is very short, while the hole density is low leading to relatively large Thomas–Fermi screening length $\lambda_{TF}$. In these materials $\lambda_{TF} \sim \xi$, which allows us to introduce field-induced effects via local changes of the parameters of the GL theory.

Let us assume the jellium model in which the electric charge of electrons is compensated by a smooth positively charged background. Both charges are restricted to the half space $x > 0$. The electric field applied to the surface is exponentially screened $E(x) = E e^{-x/\lambda_{TF}}$ inside the metal. According to the Gauss equation $\epsilon \text{div} E = \rho$, the induced electron density $\delta n = \rho/e$ reads

$$\delta n(x) = \frac{\epsilon E}{e \lambda_{TF}} e^{-x/\lambda_{TF}}. \quad (11.1)$$

In the GL equation

$$\frac{1}{2m^*} \left(-i\hbar \nabla - e^* A\right)^2 \psi + a \psi + b |\psi|^2 \psi = 0, \quad (11.2)$$