We report a large rectification effect in superconducting films in a parallel magnetic field. This rectification effect is manifested in two features in current-voltage characteristics: The critical current, $I_c$, is found to differ by as much as 40% for negative and positive currents, and beyond $I_c$, the magnitude of the voltage is different for positive and negative currents, $|V(+I)| \neq |V(-I)|$. Furthermore, the critical current difference $|I_{c+}| - |I_{c-}|$ shows complicated behavior, changing sign as temperature and magnetic field are varied. We discuss a model based on the Bean-Livingston surface barrier and inhomogeneous bulk pinning that accounts for all observed behavior.

1. INTRODUCTION

It is generally believed that the current-voltage ($IV$) characteristics of any homogeneous superconducting films are independent of the direction of current. However, this may not be true for the case of a superconducting film in field parallel to the film surface.\(^1\)\(^-\)\(^4\) Specifically, the critical current and the sample voltage are found to vary as the direction of current is reversed. This asymmetric behavior is observed in type-II superconducting films with the critical currents differing by as much as 41% between the opposite sample currents.\(^4\) We believe that the understanding of its origin not only helps to gain information on the dynamic and static properties of vortices near superconducting surfaces, but also enhances the potential of using this behavior for device purposes.

In this paper, we present detailed measurements of asymmetric $IV$ characteristics for superconducting Pb$_{0.9}$Bi$_{0.1}$ alloy in magnetic fields parallel to the surface and perpendicular to the applied current. In the superconducting mixed state, the critical current and sample voltage, characterizing the static and dynamic pinning properties of vortices respectively, both exhibit strong asymmetric behavior. Specifically, the positive
critical current $|I_{c+}|$ and negative critical current $|I_{c-}|$, which signify minimum currents required in order to move vortices across the sample from left to right (away from the substrate) and from right to left (toward the substrate) (the sign of sample current is arbitrarily chosen to show the asymmetric effect, as well as to simplify our discussion later) [Also see Fig. 1], respectively, are not equal at a non-zero parallel magnetic field. Their difference $|I_{c+}| - |I_{c-}|$ shows a complicated behavior, changing signs with the temperature and magnetic field. Generally speaking, at lower temperatures and magnetic fields, the positive critical current $|I_{c+}|$ signifying the minimum depinning current to push vortices away from the substrate, is greater than the negative critical current $|I_{c-}|$; as the magnetic fields or temperature increases, the negative critical current $|I_{c-}|$ becomes bigger. The sample voltages $|V(+I)|$ and $|V(-I)|$ show similar behavior with an added feature, namely, the voltage difference $|V(+I)| - |V(-I)|$ not only changes sign with temperature and magnetic field but also with the sample current $|I|$.

In addition, the magnitude of the asymmetry decreases as the temperature and/or magnetic field increases. Eventually, the asymmetric behavior disappears at certain temperature and magnetic field and this is usually when the $IV$ characteristics becomes linear.

We discuss a model combining the Beans-Livingston surface barrier\(^5\) and inhomogeneous bulk pinning. In the model, we assume that the surface barriers at the two superconducting interfaces, the superconductor-vacuum-interface and the superconductor-substrate-interface, are the same, since the superconducting parameters which dominate the surface barriers,