Heterodyne Detection in KPFM:
A Comparative Evaluation of Imaging Techniques

Y. Wagatsuma,[1#] C. Goto,[1,] T. Xiaowei,[1] Jongduk Kim,[1] and Jake Kim[2]

[1]*Park Systems Japan Inc.1-17-1 Kanda Nishiki-cho, Chiyodaku, Tokyo, 101-0054, Japan*
[2]*Park Systems Corporate HeadquartersKANC 15F, Gwanggyo-ro 109, Suwon 16229, Korea*
y-wagatsuma@parksystems.com

Among the various advanced techniques in atomic force microscopy (AFM), Kelvin probe force microscopy (KPFM) is one of the most widely used. Its popularity stems from its ability to provide relative measurements of a sample's surface potential and work function, making it an essential tool in both scientific research and industrial applications. Since its inception, KPFM has enabled significant progress in fields such as semiconductor research, photovoltaics, and materials science, where precise surface potential mapping is critical. In semiconductor research, for example, KPFM has been widely used to study potential distributions in metal–oxide–semiconductor field-effect transistors (MOSFETs). In photovoltaics, it has contributed to the understanding of charge separation and transport in perovskite solar cells. In materials science, KPFM has helped reveal surface electronic properties in two-dimensional materials such as graphene. Traditional KPFM approaches, particularly amplitude-modulation KPFM (AM-KPFM), have laid the foundation for measuring the contact potential difference (CPD) between the AFM tip and the sample. However, the increasing demand for higher sensitivity and spatial resolution has highlighted the limitations of AM-KPFM, including its susceptibility to noise and limited resolution. This has driven the development of more advanced techniques, such as sideband KPFM and the more recent heterodyne KPFM. Both AM and sideband KPFM operate near the cantilever's resonance frequency and rely on the bandwidth of the conventional feedback loop, which tends to degrade image quality, especially at higher scan speeds. Heterodyne KPFM, by contrast, employs a unique heterodyne frequency detection scheme that shifts the KPFM signal away from the cantilever's resonance frequency. This approach enhances both sensitivity and spatial resolution while effectively isolating the CPD signal from mechanical and background noise (**Figure 1**).

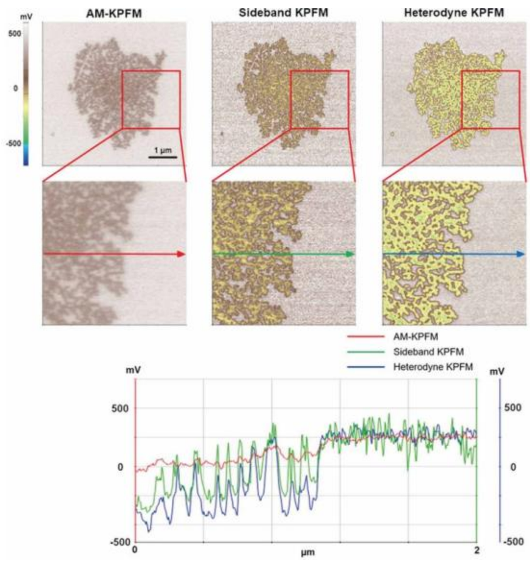

Figure 1. Surface potential images of $F_{14}H_{20}$ measured by AM, Sideband, and Heterodyne KPFM. AM-KPFM exhibits limited spatial resolution and sensitivity, Sideband KPFM shows enhanced mapping of localized potential variations, and Heterodyne KPFM achieves the highest precision and resolution, accurately resolving nanoscale differences in surface potential.