Reactive High Power Impulse Magnetron Sputtering

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Introduction

- Magnetron sputtering has been the workhorse of plasma based sputtering methods for over three decades
- For many applications a high degree of ionization of the sputtered vapor is desired
- In a high power pulsed magnetron sputtering discharge (HPPMS) discharge a high power pulse is supplied for a short period
    - low frequency
    - low duty cycle
    - low average power

  which can be split into two categories
    - high power impulse magnetron sputtering discharge (HiPIMS)
    - modulated pulse power (MPP)
- It gives high electron density and highly ionized flux of the sputtered material
- Ionized flux of sputtered vapor introduces an additional control parameter into the deposition process

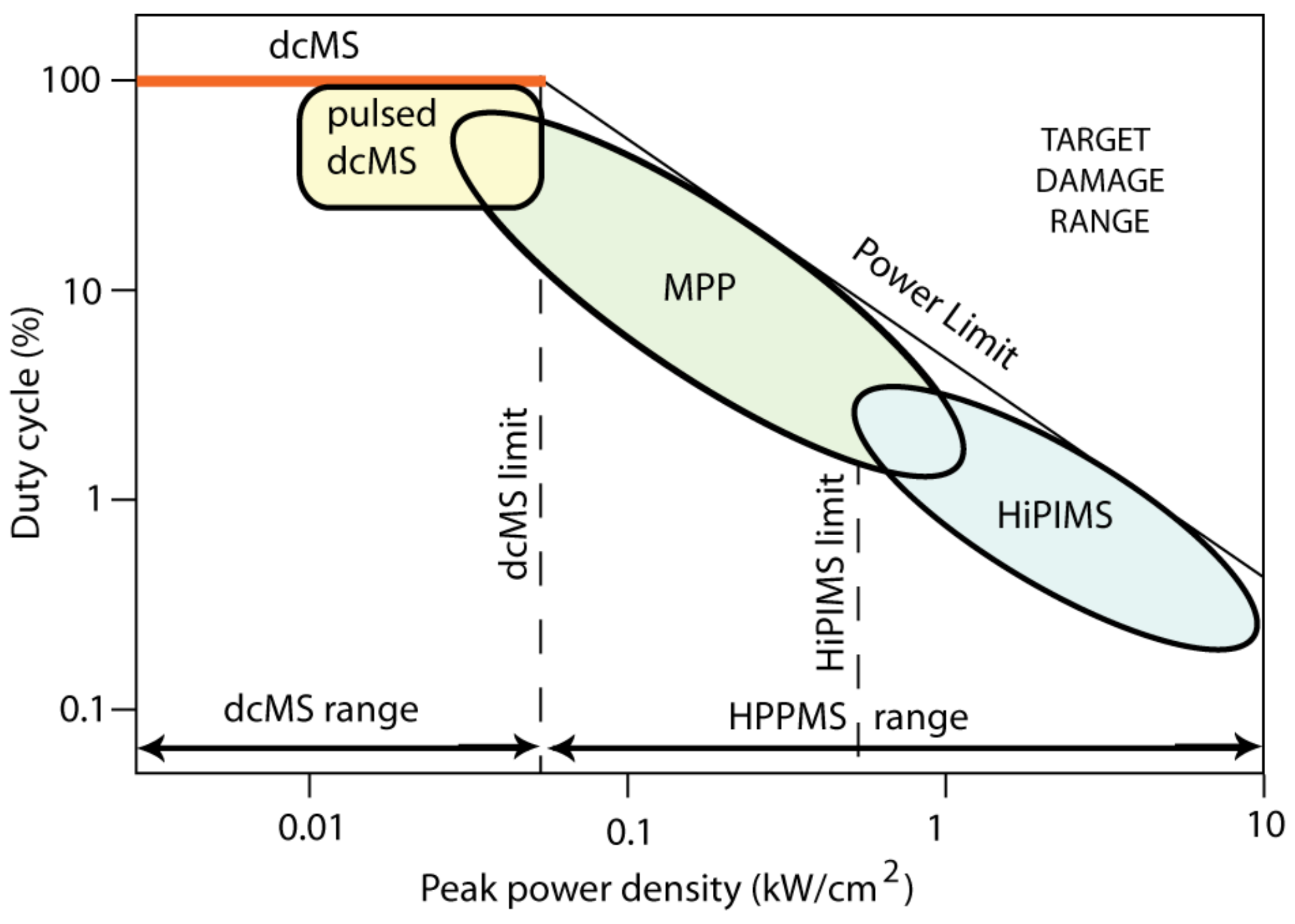

Figure 1: Nomenclature for pulsed discharges based on the peak power density at the target and the duty cycle (From Gudmundsson et al. (2012)).

Applications – reactive sputtering

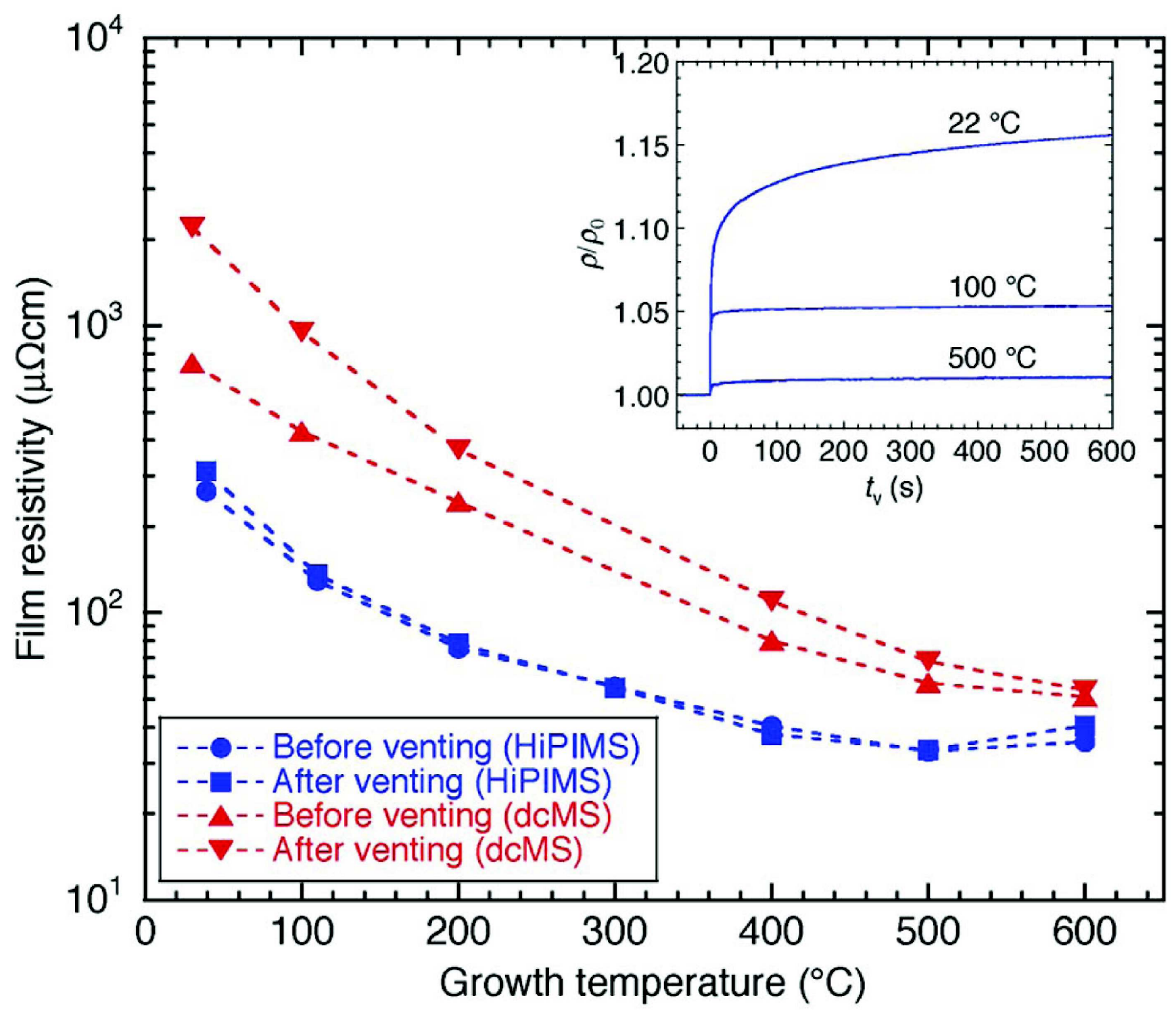

Figure 2: Room-temperature resistivity of the films (ρ_0) before and (ρ) after the chamber is vented and samples are exposed to air. ρ is obtained after 30 min of air exposure. (Inset) Fractional change in resistivity with time during the first 10 min of exposure for a subset of the films grown by HiPIMS. (From Magnus et al. (2012)).

- HiPIMS deposited films have significantly lower resistivity than dcMS deposited films on SiO_2 at all growth temperatures due to reduced grain boundary scattering
- TiN as diffusion barriers for interconnects – ultrathin continuous TiN films with superior electrical characteristics and high resistance towards oxidation can be obtained with HiPIMS at reduced temperatures (Magnus et al., 2012)

Reactive sputtering

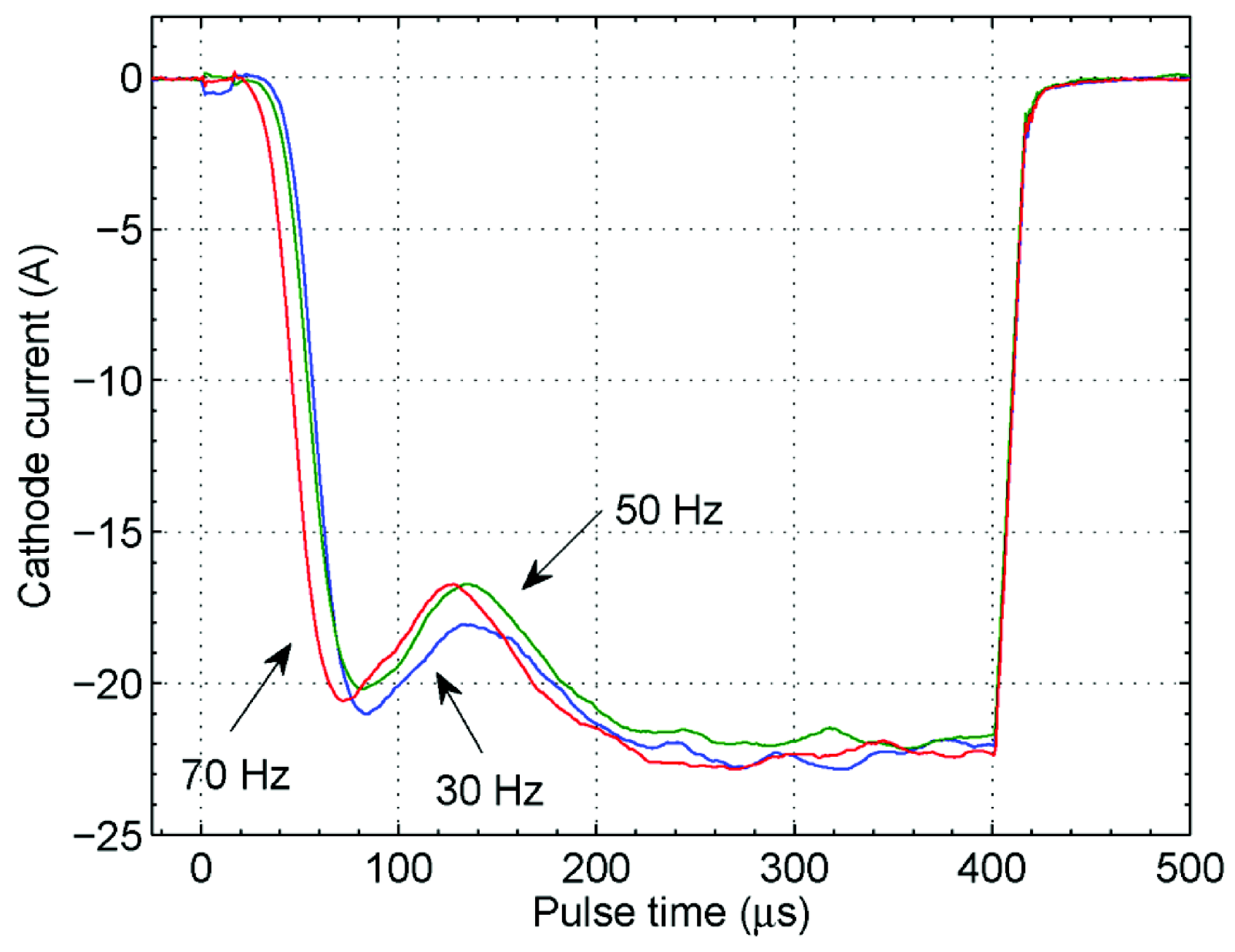

Figure 3: The discharge current waveforms for an Ar discharge with titanium target at 0.6 Pa and $V_d = 550$ for various pulse repetition frequencies. (From Magnus et al. (2011)).

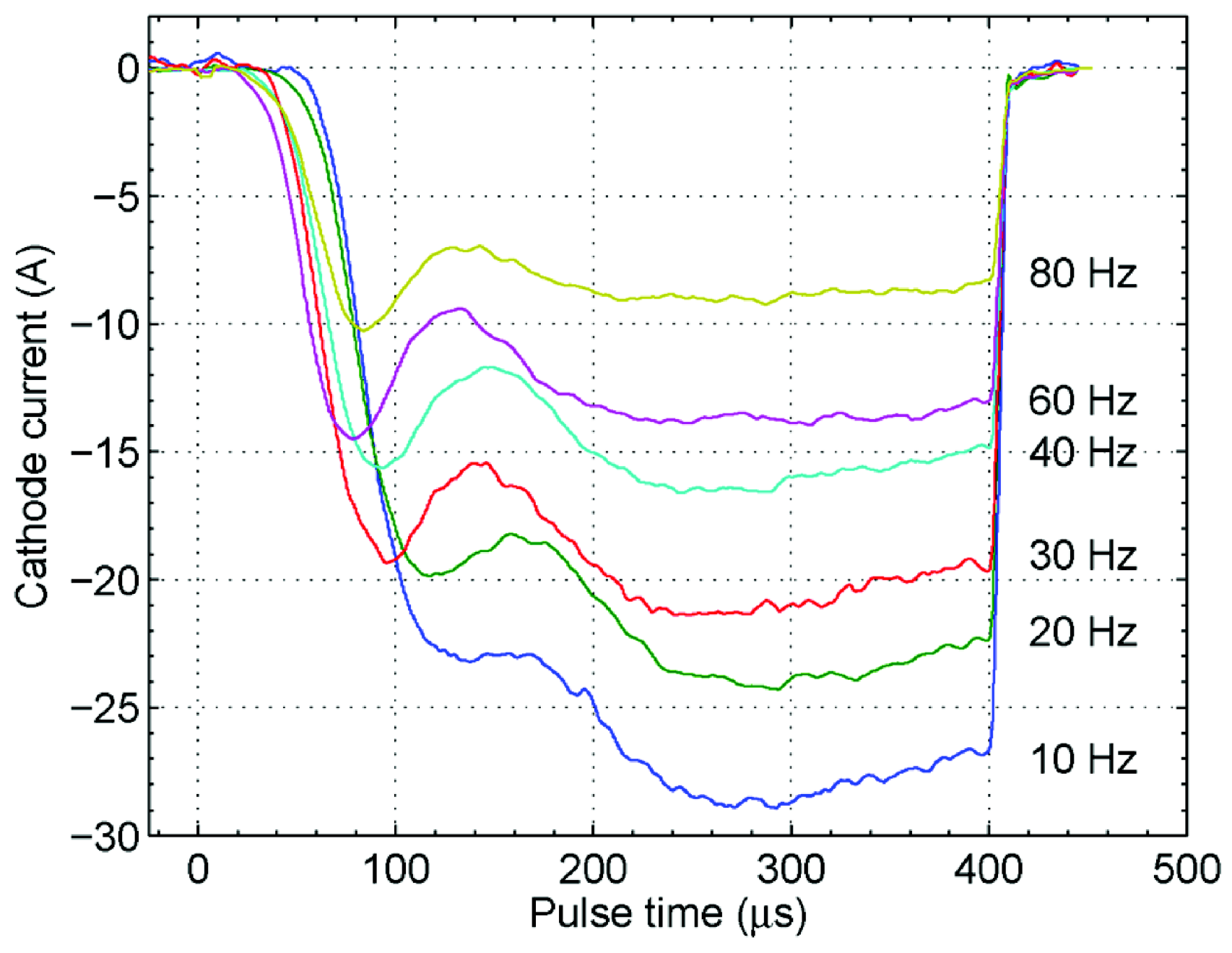

Figure 4: The discharge voltage and current waveforms for an Ar/5%-N_2 discharge with titanium target at a total pressure of 0.6 Pa and $V_d = 550$ V for a range of pulse repetition frequencies. (From Magnus et al. (2011)).

- During reactive sputtering, a reactive gas is added to the inert working gas
- The current waveform in the reactive Ar/N_2 HiPIMS discharge is highly dependent on the pulse repetition frequency, unlike for pure Ar (Magnus et al., 2011)
- N_2 addition changes the plasma composition and the target condition can also change due to the formation of a compound on its surface
- Similarly for the Ar/O_2 discharge, the current waveform is highly dependent on the repetition frequency and applied voltage which is linked to oxide formation on the target (Magnus et al., 2012)
- The current is found to increase significantly as the frequency is lowered

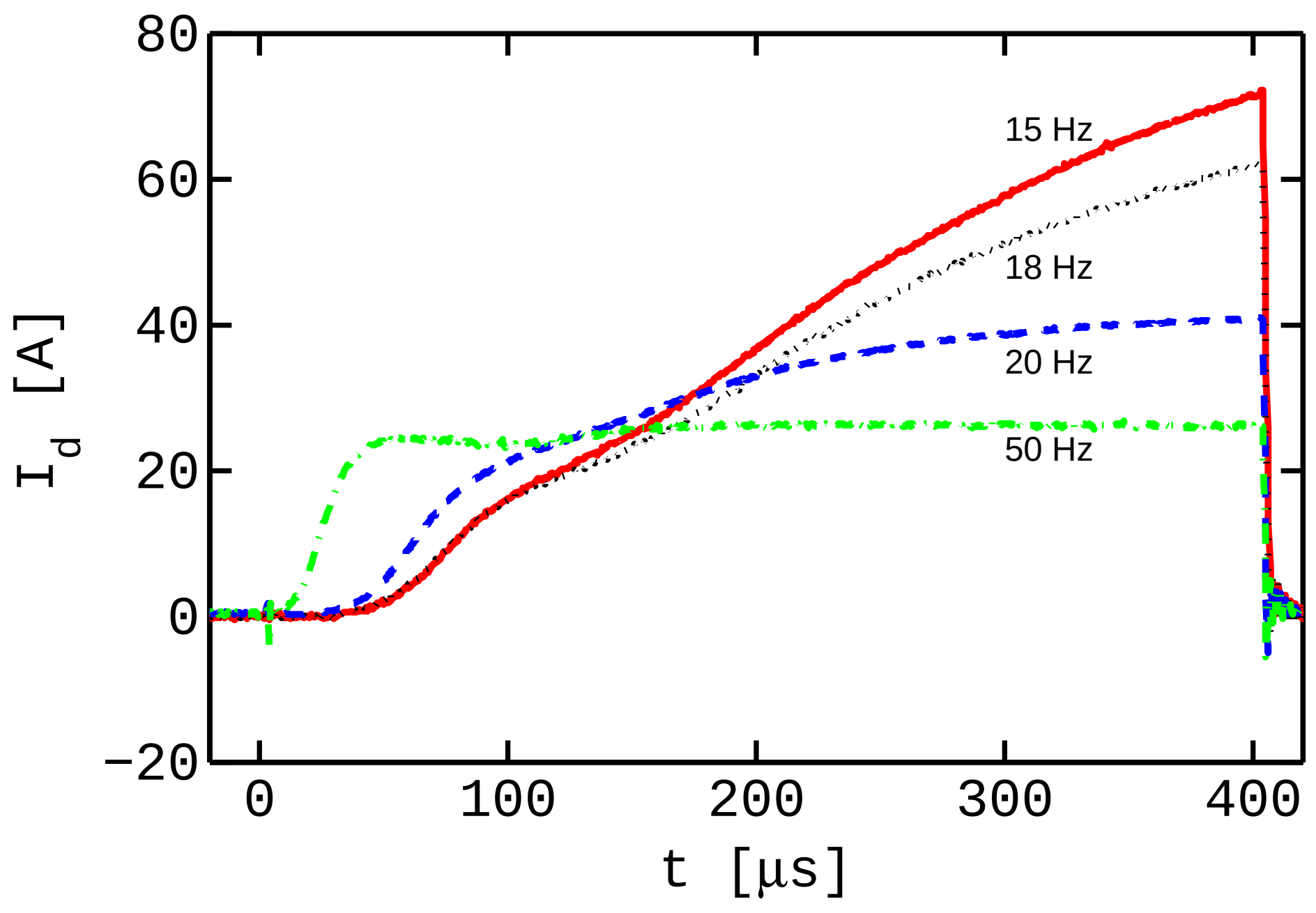

Figure 5: The discharge current for various repetition frequencies for Ar/O_2 discharge with titanium target. The discharge pressure is roughly 0.6 Pa, the oxygen flow rate 2 sccm, and the pulse voltage is 600 V.

- HiPIMS differs significantly from dcMS, due to the fact that self-sputtering quickly becomes dominant and the working gas ions (mostly Ar^+ and N_2^+ or O_2^+) are depleted from the area in front of the target, due to rarefaction
- The secondary electron emission yield is governed by the composition of the target (Ti or TiN or TiO_2) and the type of ions that are bombarding it
- γ_{SE} is practically zero for singly charged metal ions impacting a target of the same metal

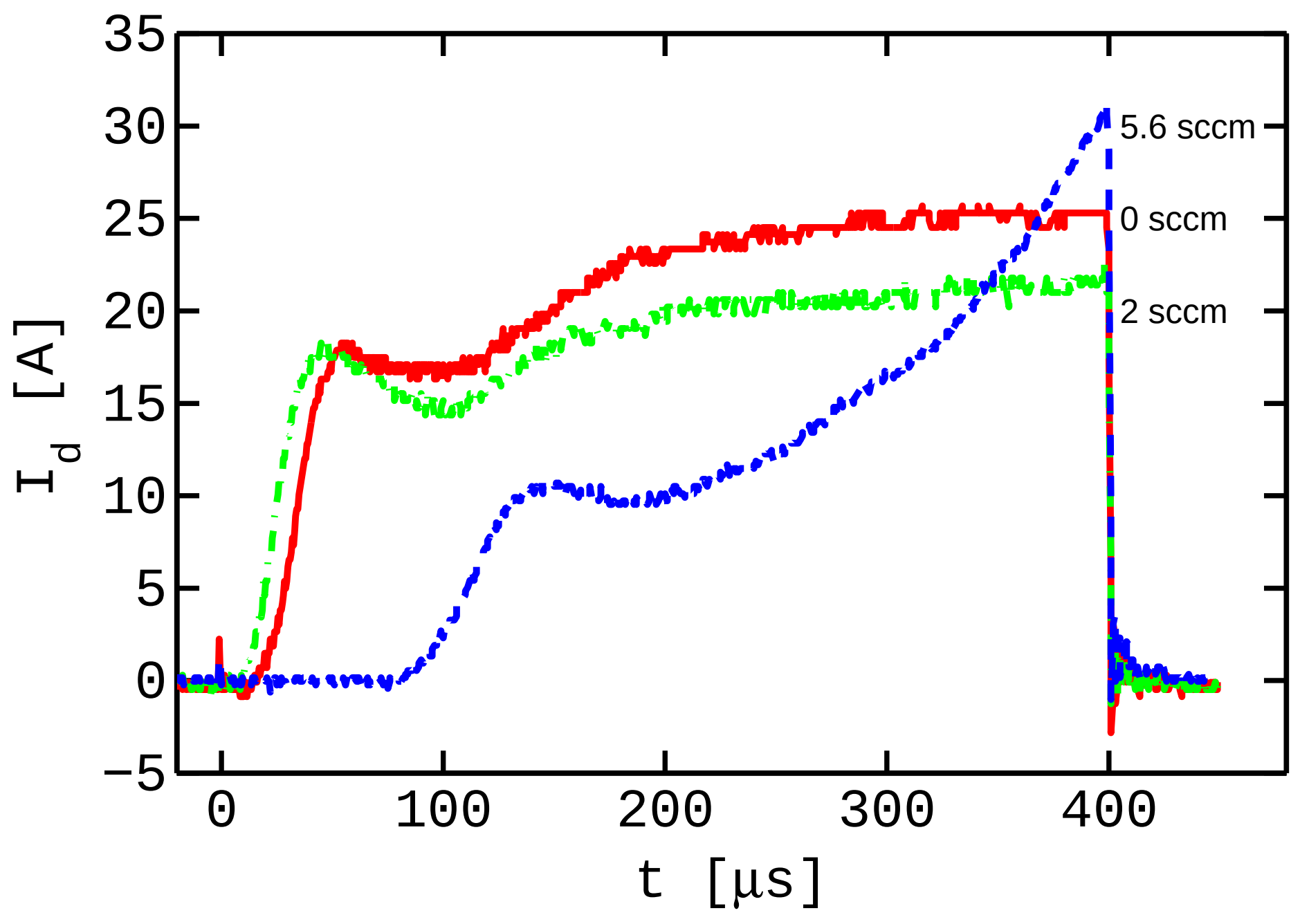

Figure 6: The discharge current for various oxygen flow rates for Ar/O_2 discharge with titanium target. The discharge pressure is roughly 0.6 Pa, the repetition frequency 50 Hz, and the pulse voltage is 600 V.

- γ_{SE} will be higher for self sputtering from a TiN or TiO_2 target, where N^+-ions or O^+-ions are also present, than for self-sputtering from a Ti target, where multiply charged Ti ions are needed to create secondary electrons
- At high frequencies, nitride or oxide is not able to form between pulses, and self-sputtering by Ti^+-ions (singly and multiply charged) from a Ti target is the dominant process
- At low frequency, the long off-time results in a nitride or oxide layer being formed on the target surface and self-sputtering by Ti^+- and N^+-ions or O^+-ions from TiN or TiO_2 takes place
- As the oxygen flow is increased a transition to oxide mode is observed as seen in Figure 6 – The delay in the onset of the current increases, the initial current peak is lowered and a transition to a self-sputtering runaway occurs
- It has been confirmed that in the oxide mode, the discharge is dominated by O^+-ions, due to oxygen atoms sputtered off the target surface (Aiempanakit et al., 2013)

Summary

- The current-voltage-time waveforms in a reactive discharge exhibit similar general characteristics as the non-reactive case
    - the current rises to a peak, then decays because of rarefaction before rising to a self-sputtering dominated phase
- The secondary electron emission yield is higher for a nitride or oxide target than a titanium target when self-sputtering is the dominant sputtering mechanism
- At low repetition frequency, the long off-time results in a nitride or oxide layer being formed on the target surface and self-sputtering by Ti^+ and N^+ or O^+-ions from TiN or TiO_2 takes place with an increase in secondary electron emission yield and a corresponding increase in discharge current

Acknowledgments

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