

# Chlorine Based RIE-ICP of Single Crystal Silicon and Polysilicon

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# Etch Mechanisms

- Dissociation of molecular chlorine into atomic chlorine ( $\text{Cl}_2 \rightarrow \text{Cl}$ )
- Adsorption of atomic chlorine onto the silicon surface
- Product formation is not spontaneous (as in Si-F chemistry) and the reaction has a low probability unless the surface is damaged or the bonds are broken by ion bombardment

# Si-Cl etch mechanisms cont.

- Etch is reaction rate limited once the surface is saturated with adsorbed Cl – steric hindrance
- Ion bombardment needed not only for product formation but also to create new sites for adsorption.
- Increasing the ICP source power increases the amount of dissociation and the ion density.
- Increasing the electrode RIE power increases the ion energy above a necessary threshold for product formation.
- Profiles are anisotropic due to the need for ion bombardment.

# Role of Si-Cl Etch Chemistry

- $\text{Cl}_2$  is the dominant etch species (can be derived from  $\text{Cl}_2$ ,  $\text{BCl}_3$ ,  $\text{SiCl}_4$ , etc)
- $\text{BCl}_3$  is added because it effectively etches native oxide, dehydrates the chamber and the surface, and contributes greatly to the overall ion density in the plasma. Aids in sidewall passivation by formation of boron oxide.
- Ar can be added as an additional contributor to ion bombardment
- $\text{H}_2$  can be added to control the Cl concentration and may act as a sidewall passivation agent.
- $\text{O}_2$  can be added to increase the selectivity to silicon oxide-especially important for a gate etch.

# Etch parameter influences

- Increasing the total gas flow increases the etch rate and reduces redeposition on the surface
- Increasing the ion energy and density increases the etch rate by increasing the physical and chemical components.
- Increasing the pressure may increase the supply of etchant (Cl) but may cause redeposition and surface roughening.

# Etch parameter influences

- Adjustments in the source and electrode powers affect the overall Ion Angle Distribution (IAD).
- IAD is responsible for many of the artifacts seen in the Si-Cl system such as faceting, trenching, and bowing.
- Increasing the ICP power increases the ion density and the IAD, worsening the trenching and faceting.
- Increasing the RIE power increases the ion energy and DC bias, but decreases the IAD.
- Increasing the [Cl] in the gas phase increases the amount of trenching, with an enhancement at the corners. Adsorbed surface migration is the cause.

# Etch Parameter Influences

- In RIE (low density  $10^9$ - $10^{10}$  ions/cm<sup>3</sup>), IAD broadening occurs thru ion-neutral collisions and charge exchange reactions during sheath transport
- In ICP (high density  $10^{11}$ - $10^{12}$  ions/cm<sup>3</sup>), due to low pressures and large mfp's, sheath collisions do not contribute to IAD broadening.
- IAD is typically  $1$ - $5^\circ$ , large number of ions and some hyperthermal neutrals strike the sidewall at grazing incidence and are specularly reflected.

# Etch parameter influences

- ARDE: neutral starved due to geometric shadowing or recombination at the sidewalls
- Faceting severity increases with source power and increases with decreasing pressure
- Sidewall bowing increases with pressure
- IAD and angular dependence of the sputter yield are responsible for faceting, sidewall bowing, and trenching.
- Changes in the neutral/ion flux ratio are responsible for determining the angular dependence of the etch yields and the profile evolution.

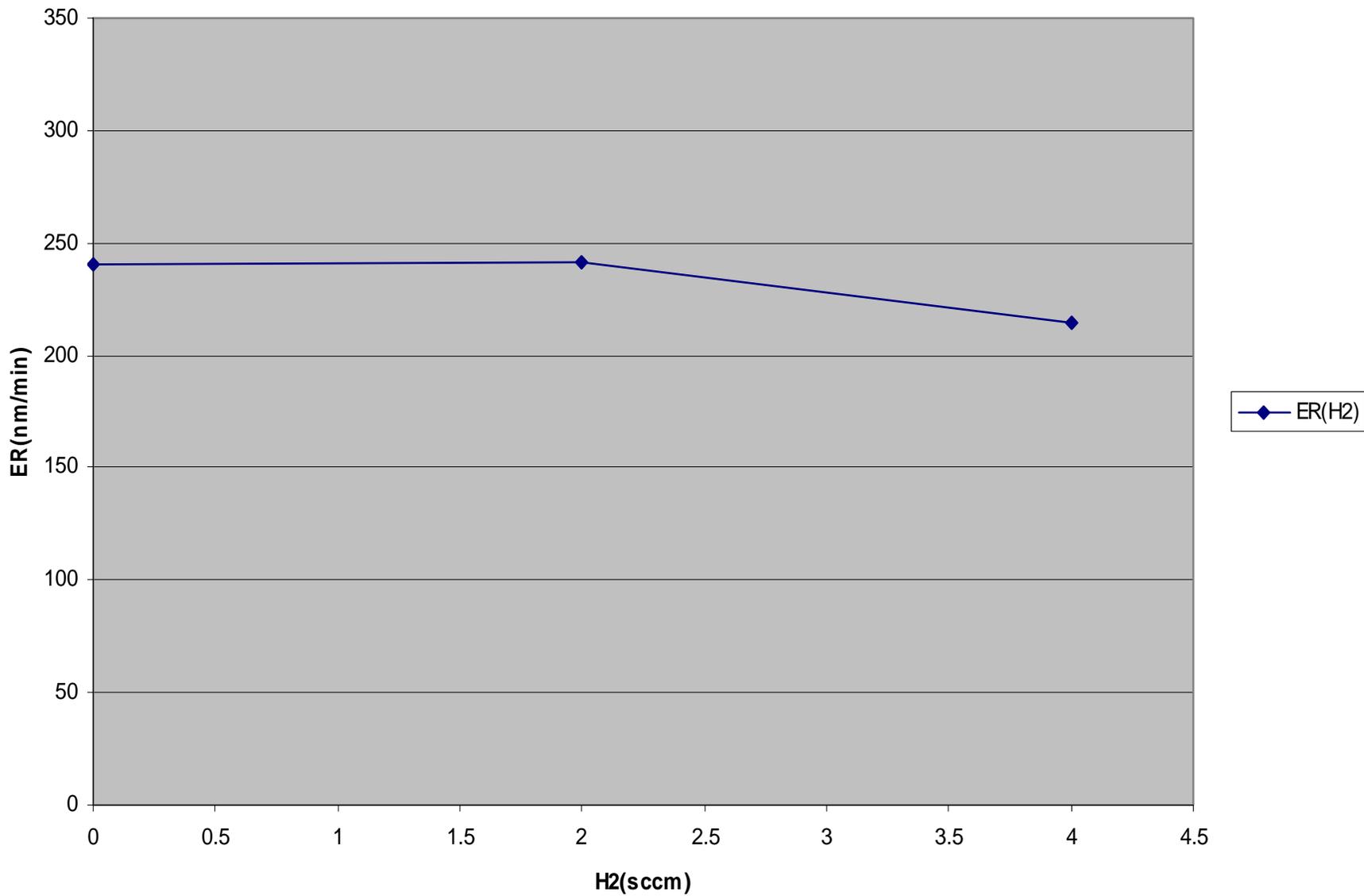
# Other influences

- $\text{SiO}_2$  mask provides enhanced selectivity in the chlorine chemistry.
- Differential charging of insulating masks can influence ion directionality resulting in artifacts.
- Resist mask can promote sidewall passivation through erosion mechanism
- Resist mask decreases selectivity to an underlying oxide layer (important for gate etch).
- Any carbon contamination in the chamber will contribute to lower oxide selectivity

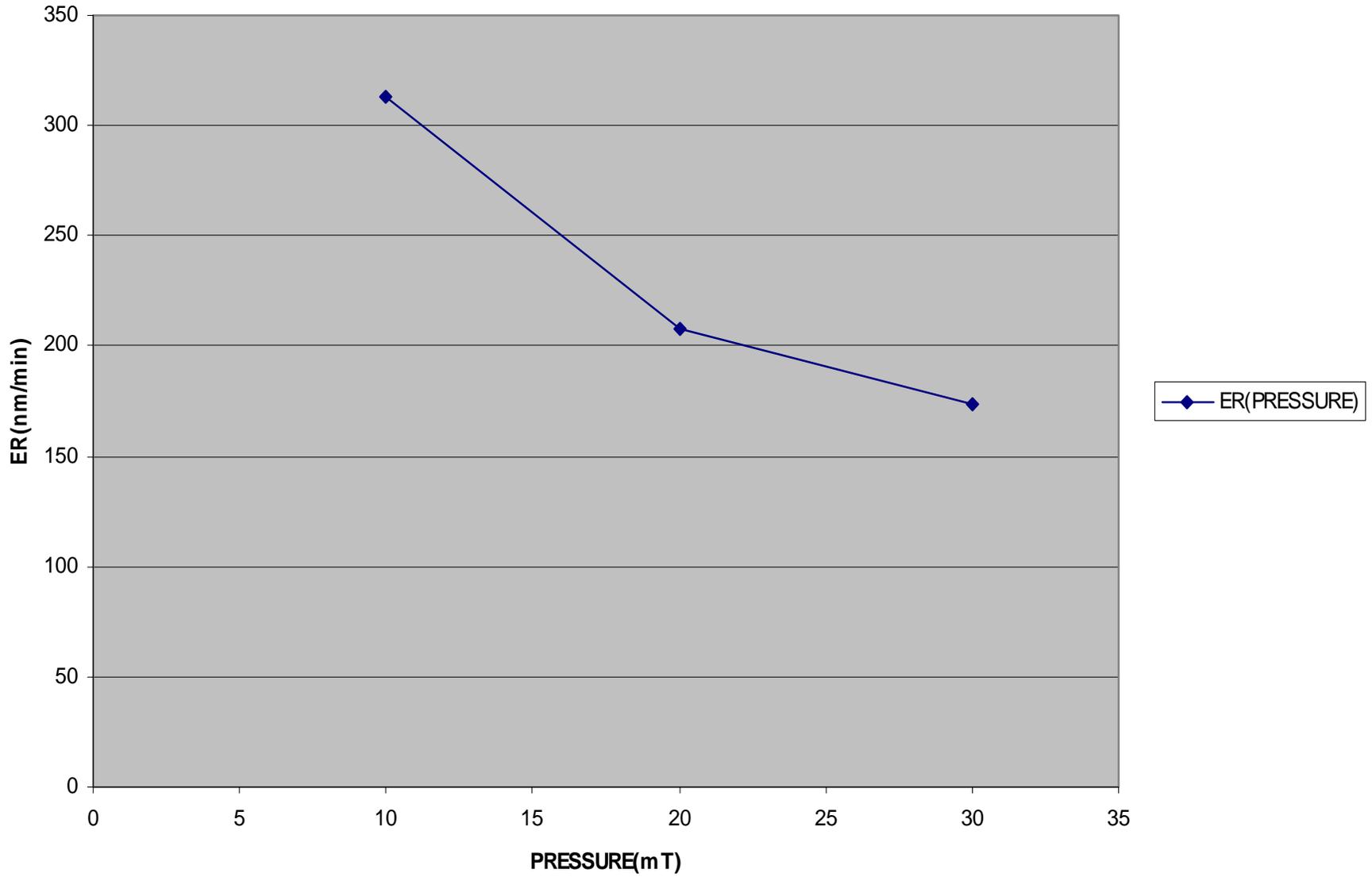
# Single xtal silicon DOE

- Factors: H<sub>2</sub> content 0-4 sccm  
pressure 10-30mT  
RIE power: 45-85W  
ICP power: 800-900W
- Cl<sub>2</sub> fixed at 70 sccm, BCl<sub>3</sub> fixed at 2sccm
- Level settings:  
H<sub>2</sub>: 0, 2, 4 sccm  
Pressure: 10, 20, 30mT  
RIE: 45, 65, 85W  
ICP: 800, 850, 900W
- ER influence: pressure, RIE, ICP, H<sub>2</sub>
- SEL influence: pressure, RIE-ICP, H<sub>2</sub>
- ER max: pressure=10mT, RIE=85W, ICP=900W, H<sub>2</sub>=0
- SEL max: pressure=30mT, RIE=85W, ICP=800W, H<sub>2</sub>=0

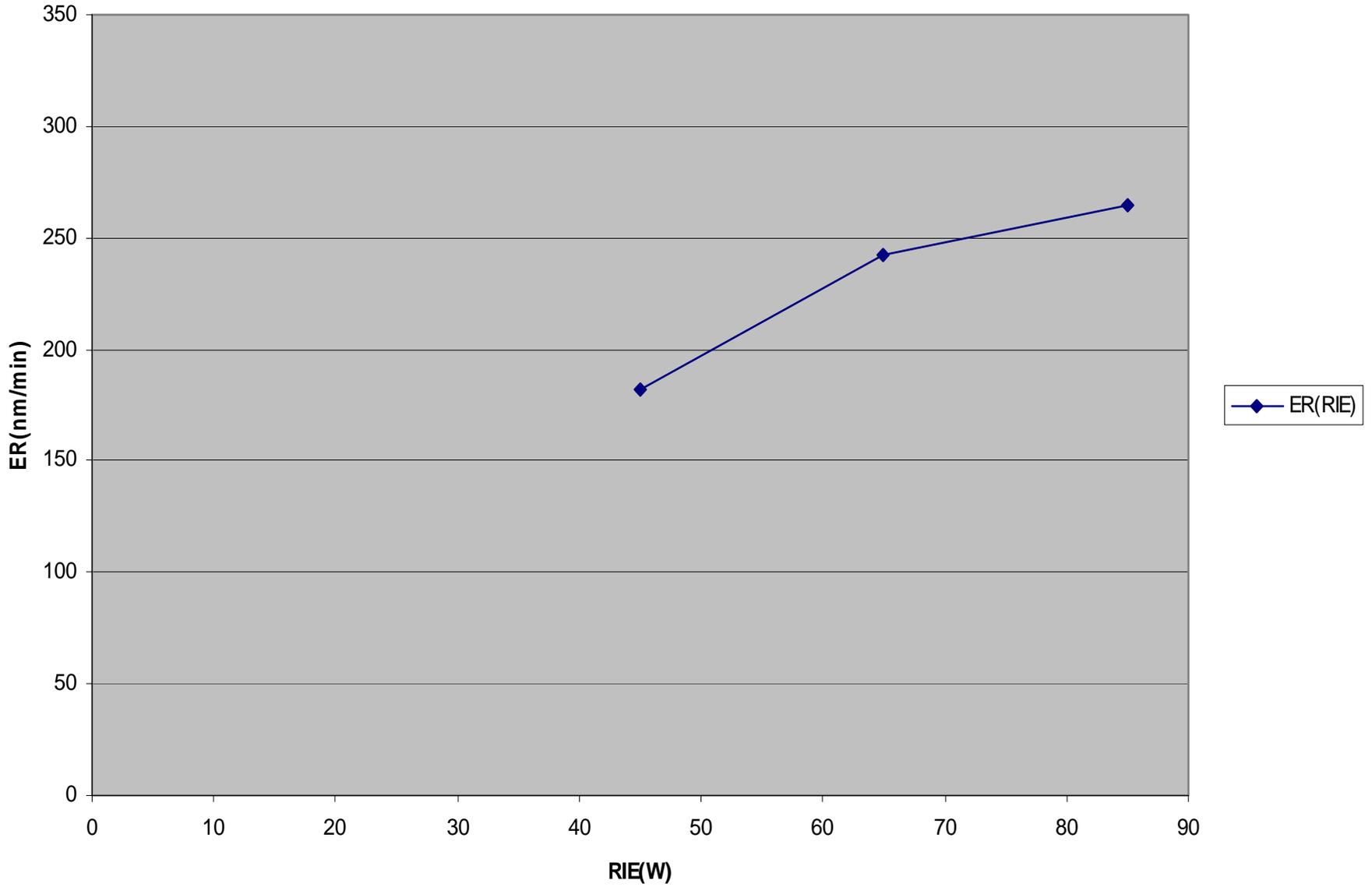
# ER(H2)



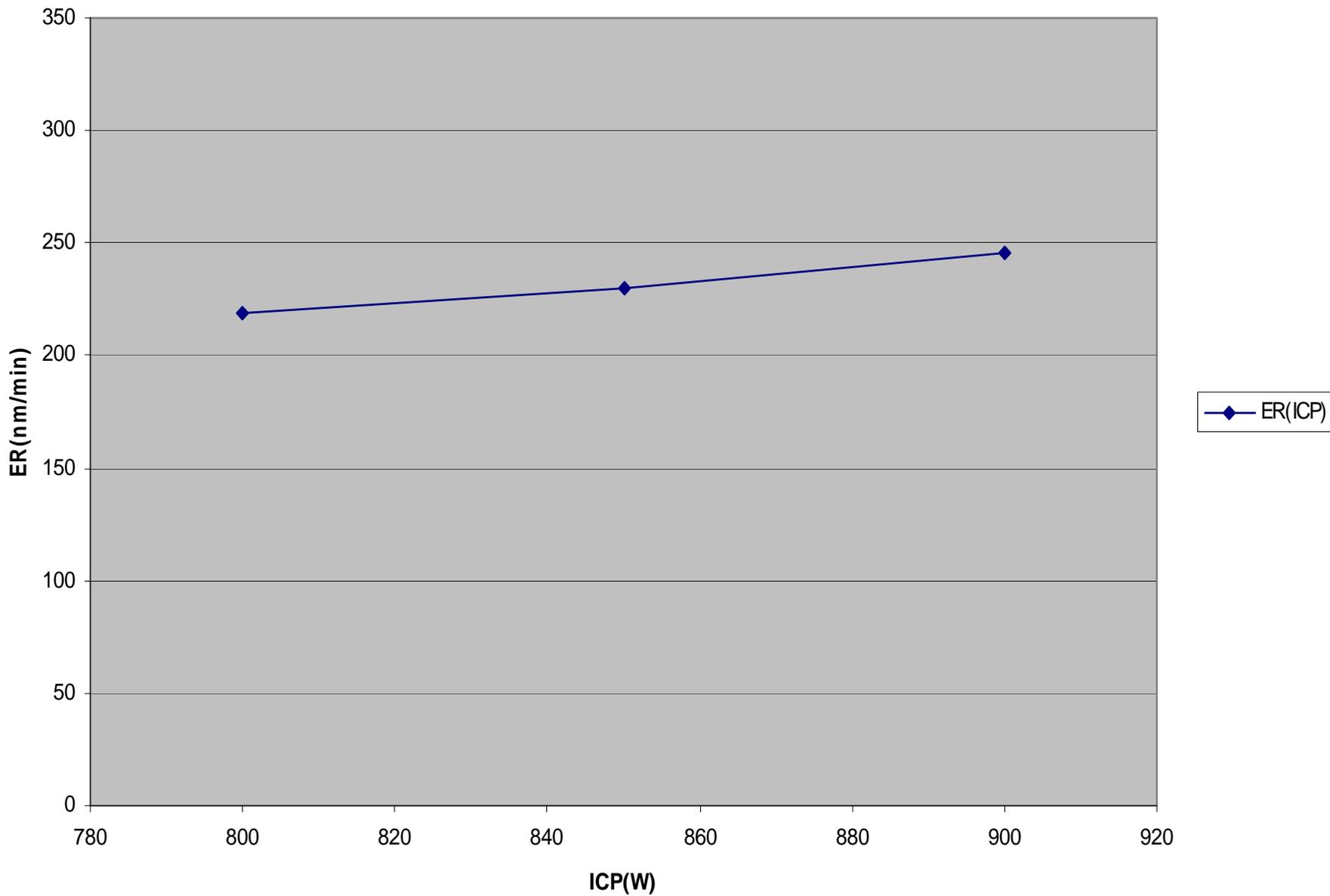
ER(PRESSURE)



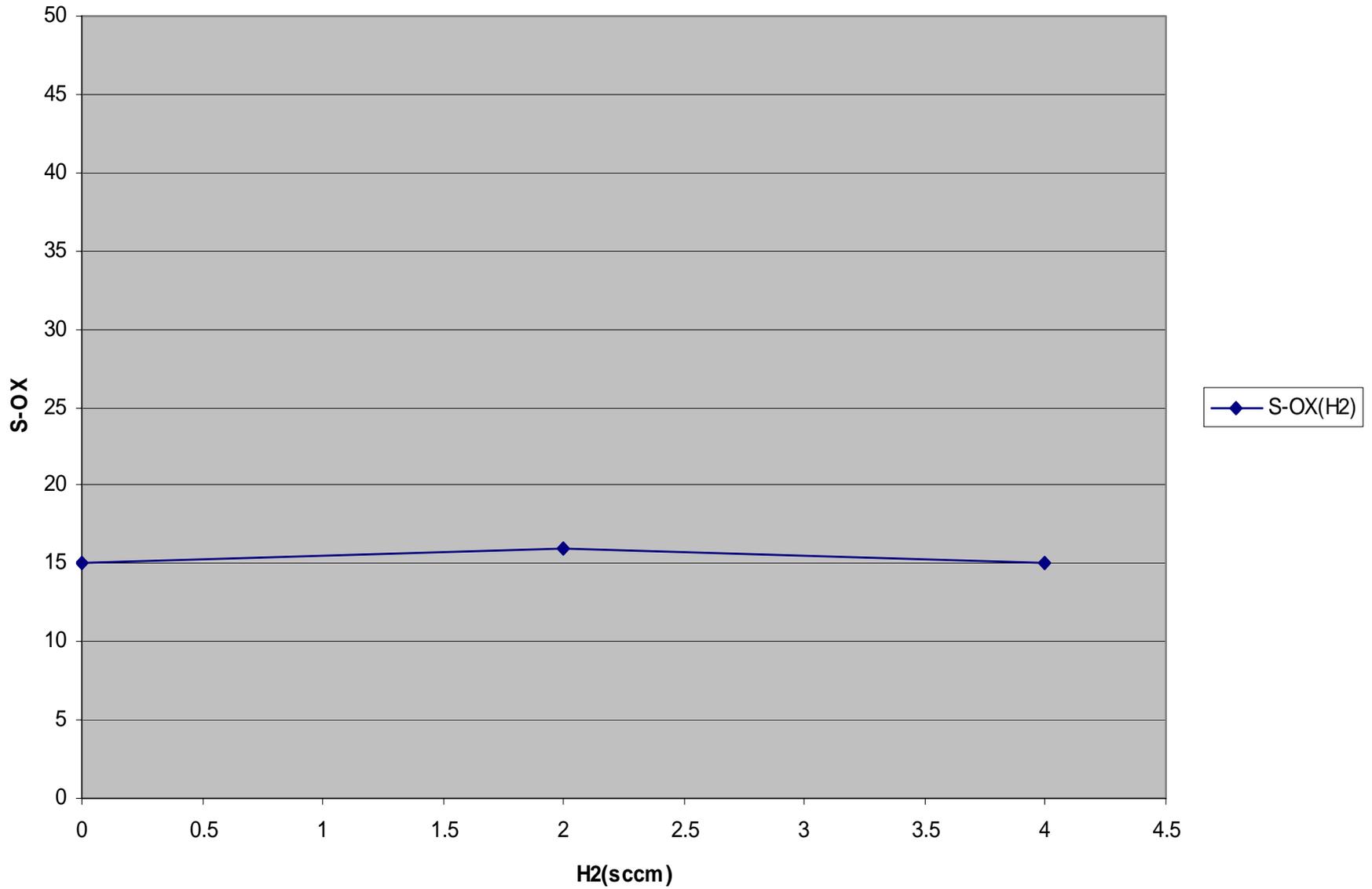
# ER(RIE)



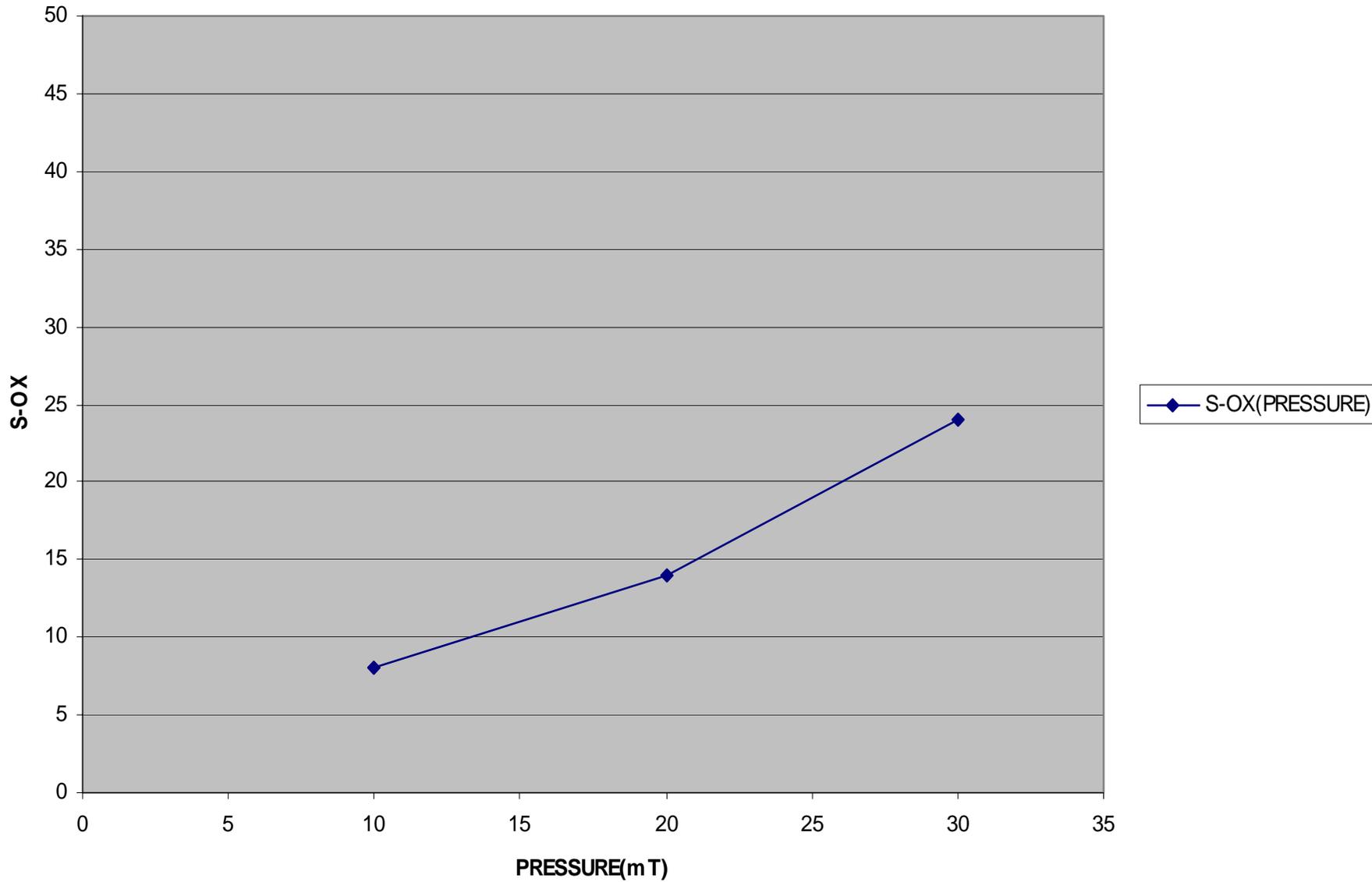
ER(ICP)



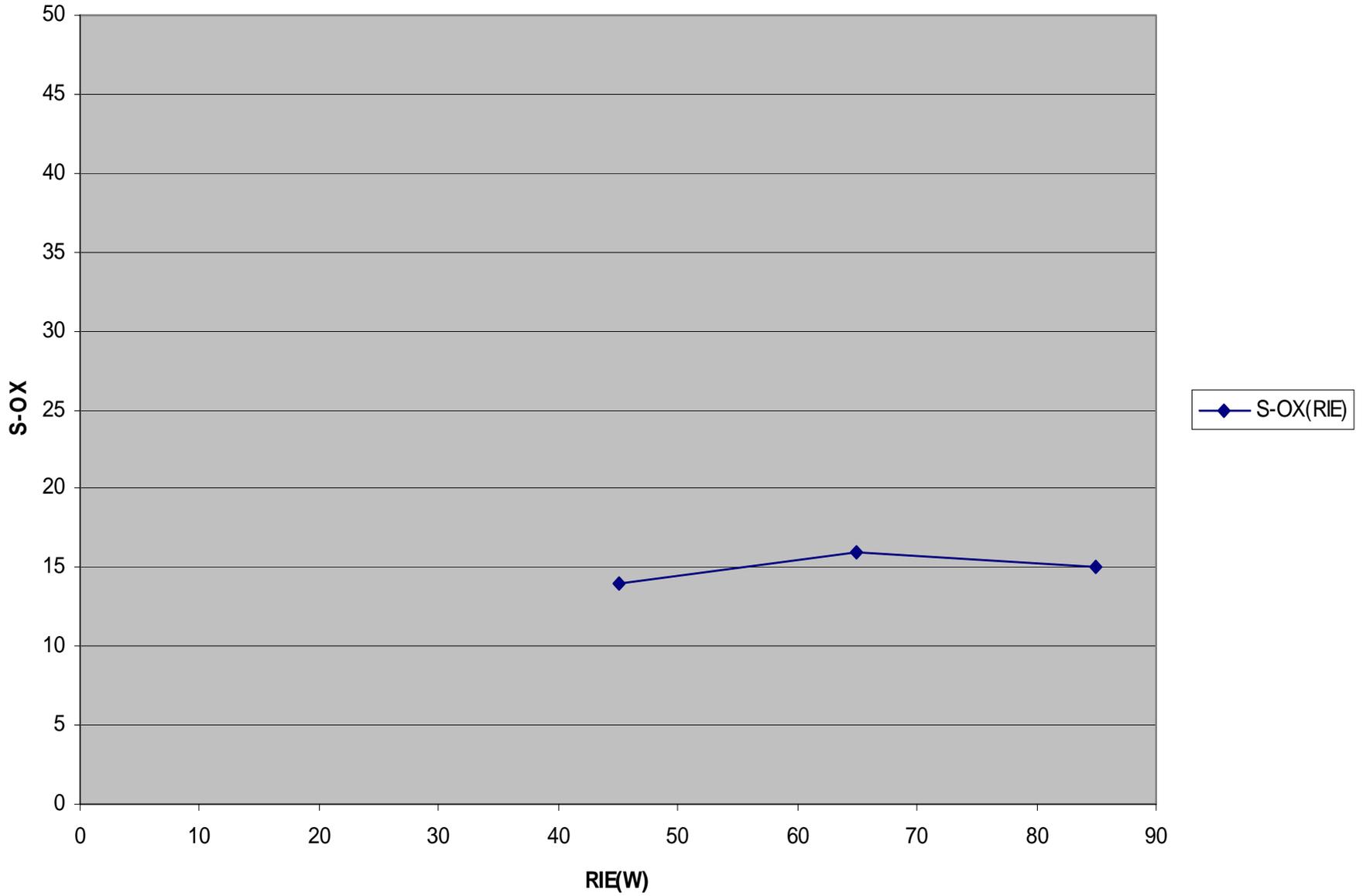
S-OX(H2)



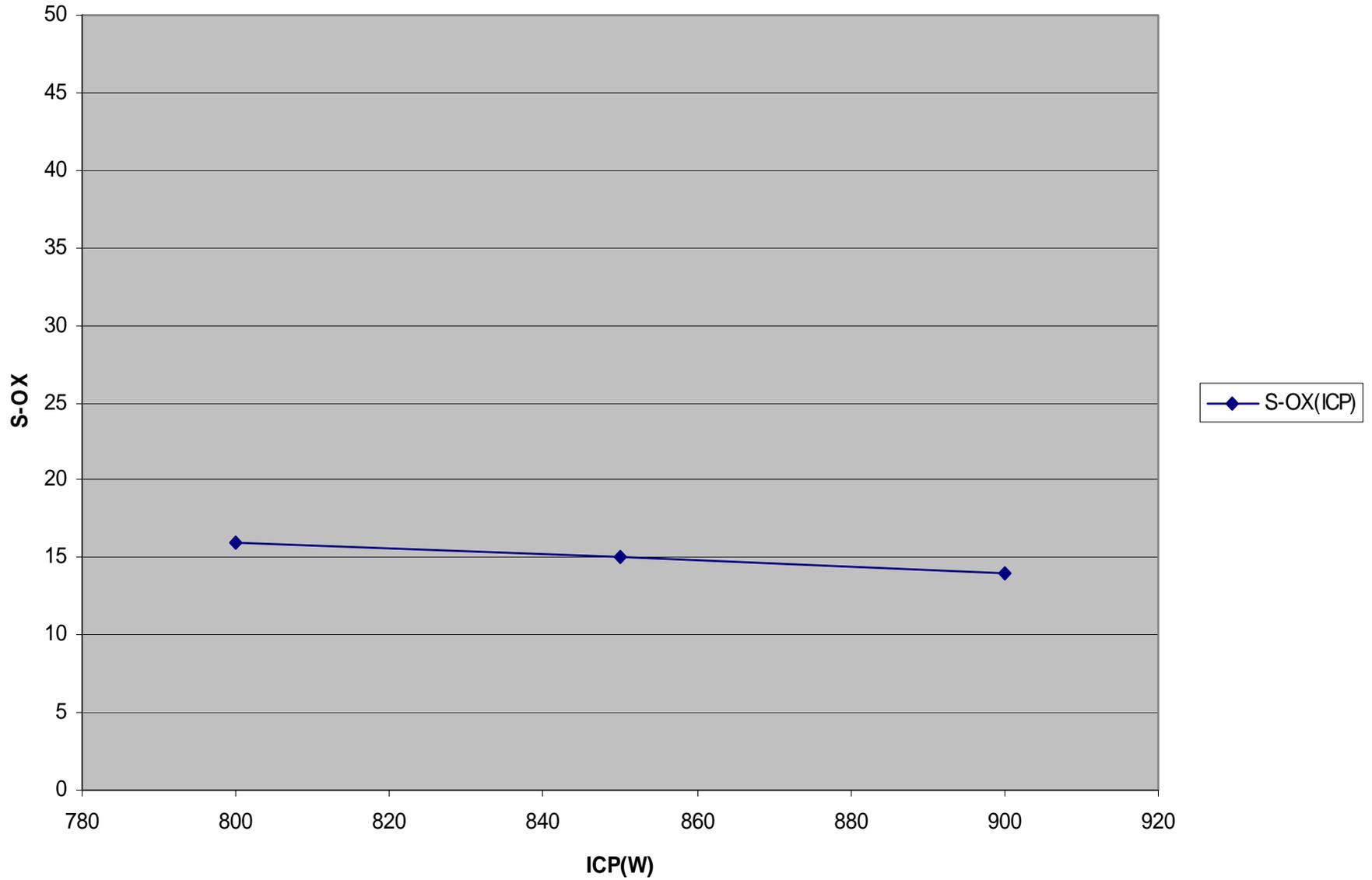
S-OX(PRESSURE)



S-OX(RIE)



S-OX(ICP)



# Recombination effects

- Cl based plasmas are especially sensitive to chamber wall conditions.
- Atomic chlorine has a great desire to recombine to form molecular chlorine.
- The preferential location for recombination is on the chamber walls. (especially for a cleaned chamber surface)
- Recombination losses of atomic chlorine lead to concentration gradients and etch rate non-uniformities.

# More recombination effects

- Although recombination is inevitable, its location should be constant for process stability.
- As etch product formation takes place, a  $\text{SiO}_x\text{Cl}_y$  layer forms on the chamber walls and limits further recombination (the case for a seasoned chamber)
- Chamber cleaning with  $\text{SF}_6/\text{O}_2$  shifts its location to the chamber walls.
- Chamber seasoning with the desired etch chemistry forces recombination at the wafer surface and enhances process stability.
- Radial distribution of  $[\text{Cl}]$  on the wafer peaks at the center of the wafer when recombination at the walls is dominant leading to etch rate non-uniformity.

# Dopant effects on the etching of silicon

- Dopant type and concentration can affect silicon reaction rates
- N-doped silicon etches more rapidly than undoped or p-doped silicon in Cl based discharges
- Charge transfer is responsible for higher N+ etch rate. Raised  $E_F$  permits more efficient charge transfer from Si to Cl(ads) forming an ionic bond and opening sites for Cl adsorption → etching
- On undoped Si, Cl is covalently bonded sterically inhibiting further chemisorption and lattice penetration → low reaction rate

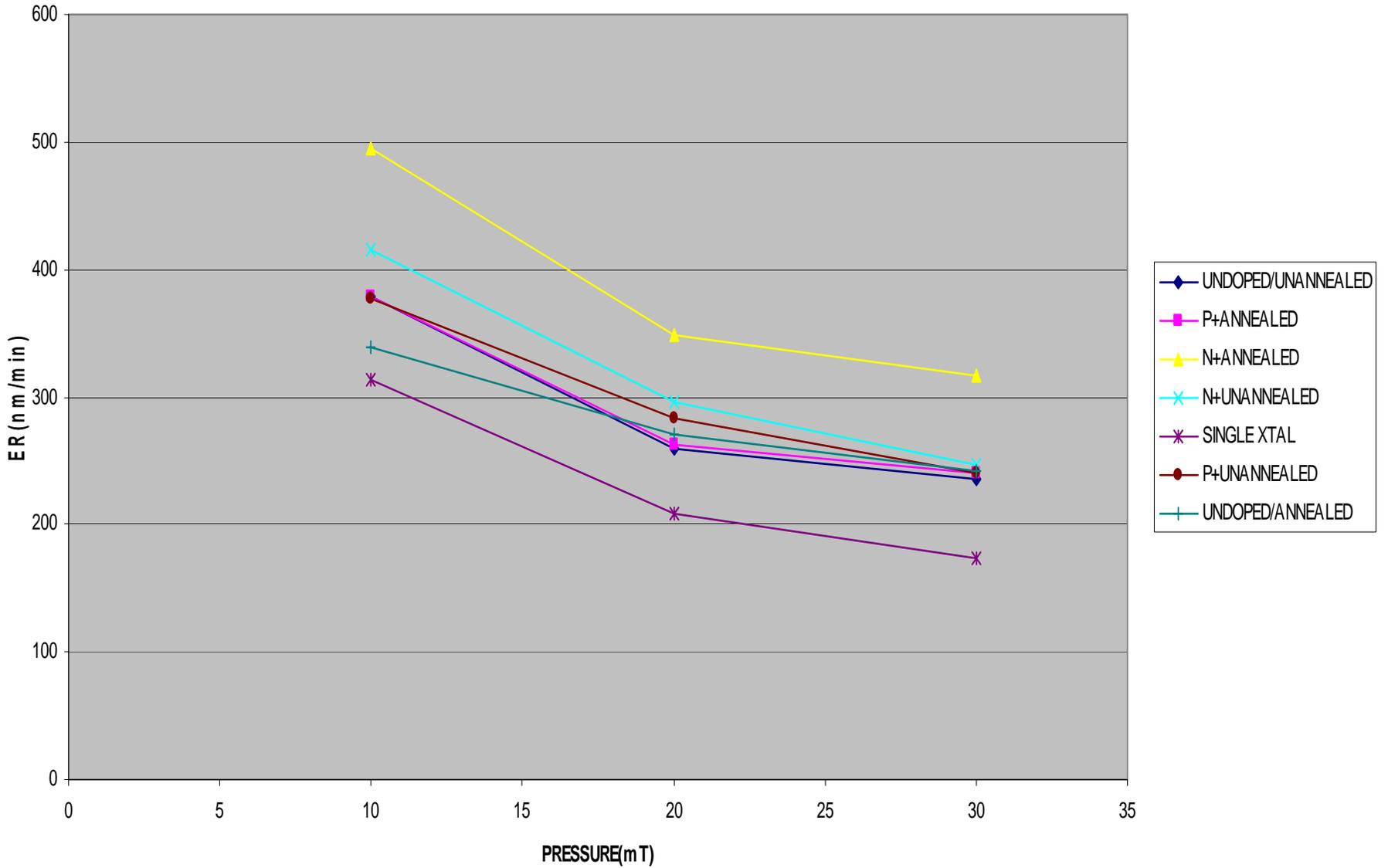
# Dopant effects on silicon etching

- The chemical nature of the n-type dopant has no effect on the etch rate
- Active carrier concentration correlates with etch rate
- Unactivated n-type species do not enhance etching
- Steric hindrance on close packed surfaces (111) can impede Cl chemisorption
- On undoped and p-type silicon, principal reaction products are unsaturated SiCl and SiCl<sub>2</sub>, while for n-type the SiCl<sub>4</sub> is dominant.

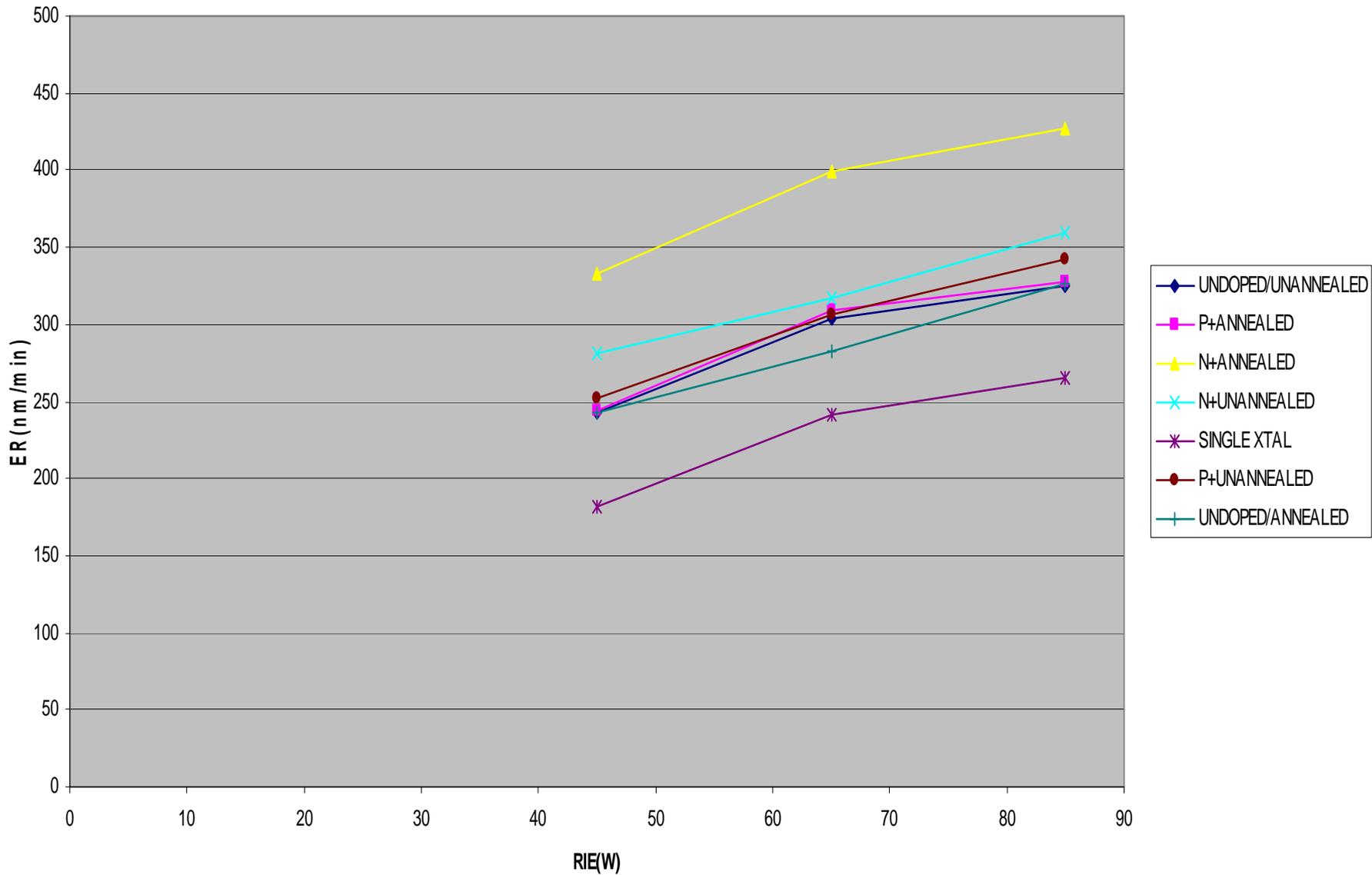
# Polysilicon DOE

- Factors: H<sub>2</sub> content 0-4sccm  
pressure: 10-30mT  
RIE: 45-85W  
ICP: 800-900W
- Cl<sub>2</sub> fixed at 70sccm, BCl<sub>3</sub> fixed at 2sccm
- Level settings:  
H<sub>2</sub>: 0, 2, 4 sccm  
Pressure: 10, 20, 30mT  
RIE: 45, 65, 85W  
ICP: 800, 850, 900W
- ER influence: Pressure, RIE (all types, annealed or not)
- SEL influence: Pressure
- ER:N+(annealed/unannealed) >P+(unannealed/annealed)>undoped  
(unannealed/annealed)> single crystal

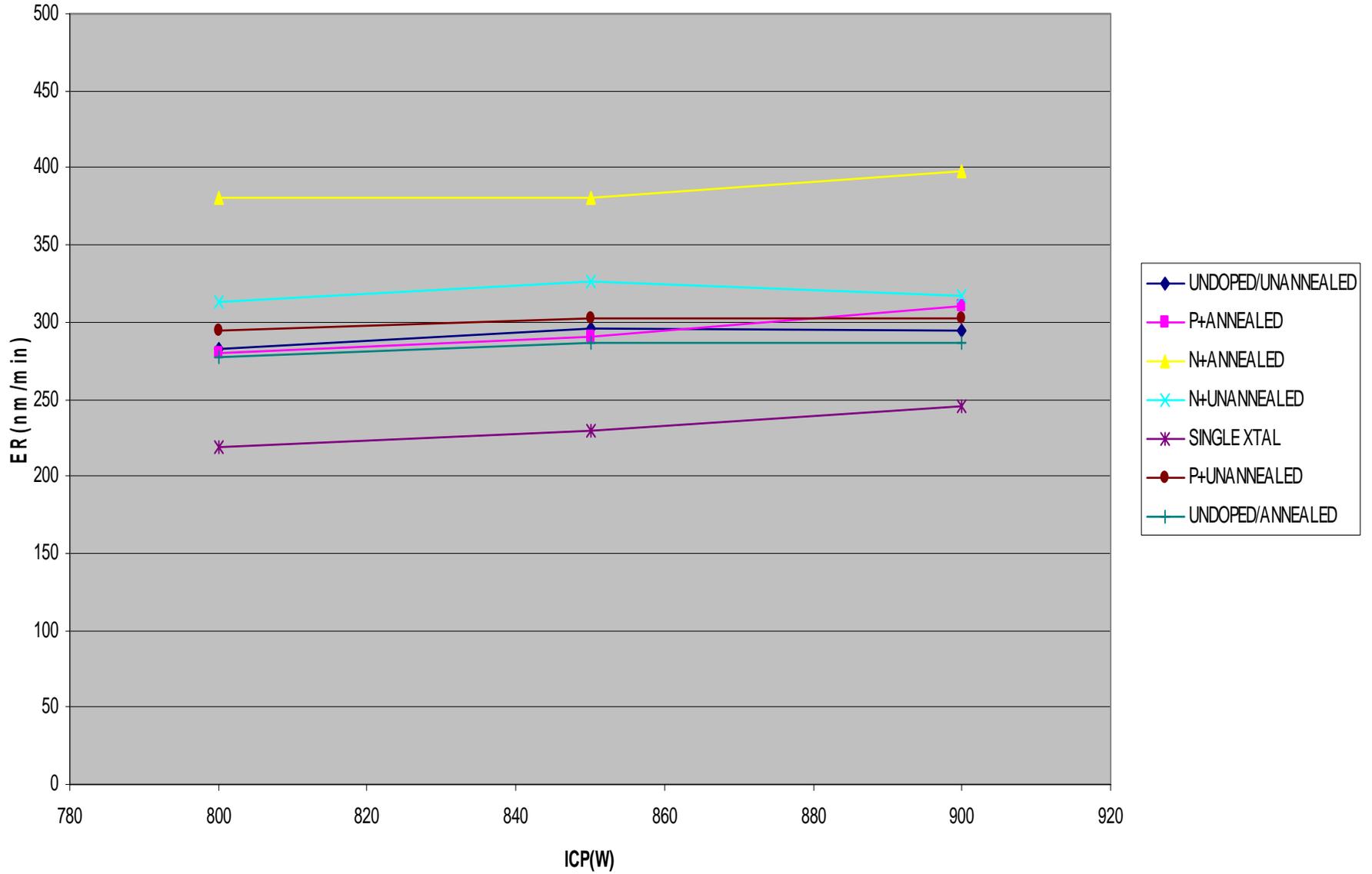
# POLY/SXTAL ER(PRESSURE)



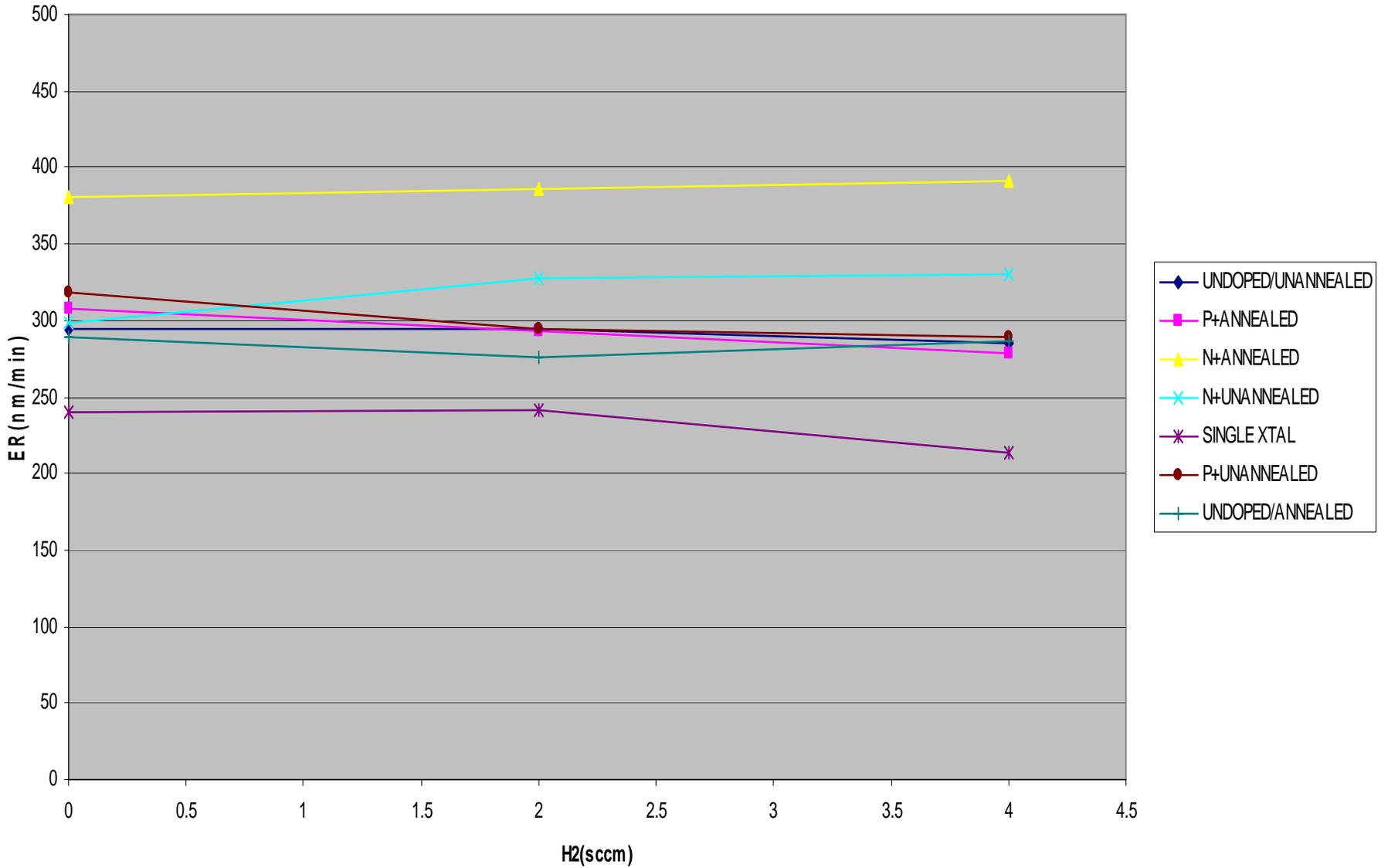
# POLY/S-XTAL ER(RIE)



# POLY/S-XTAL ER(ICP)



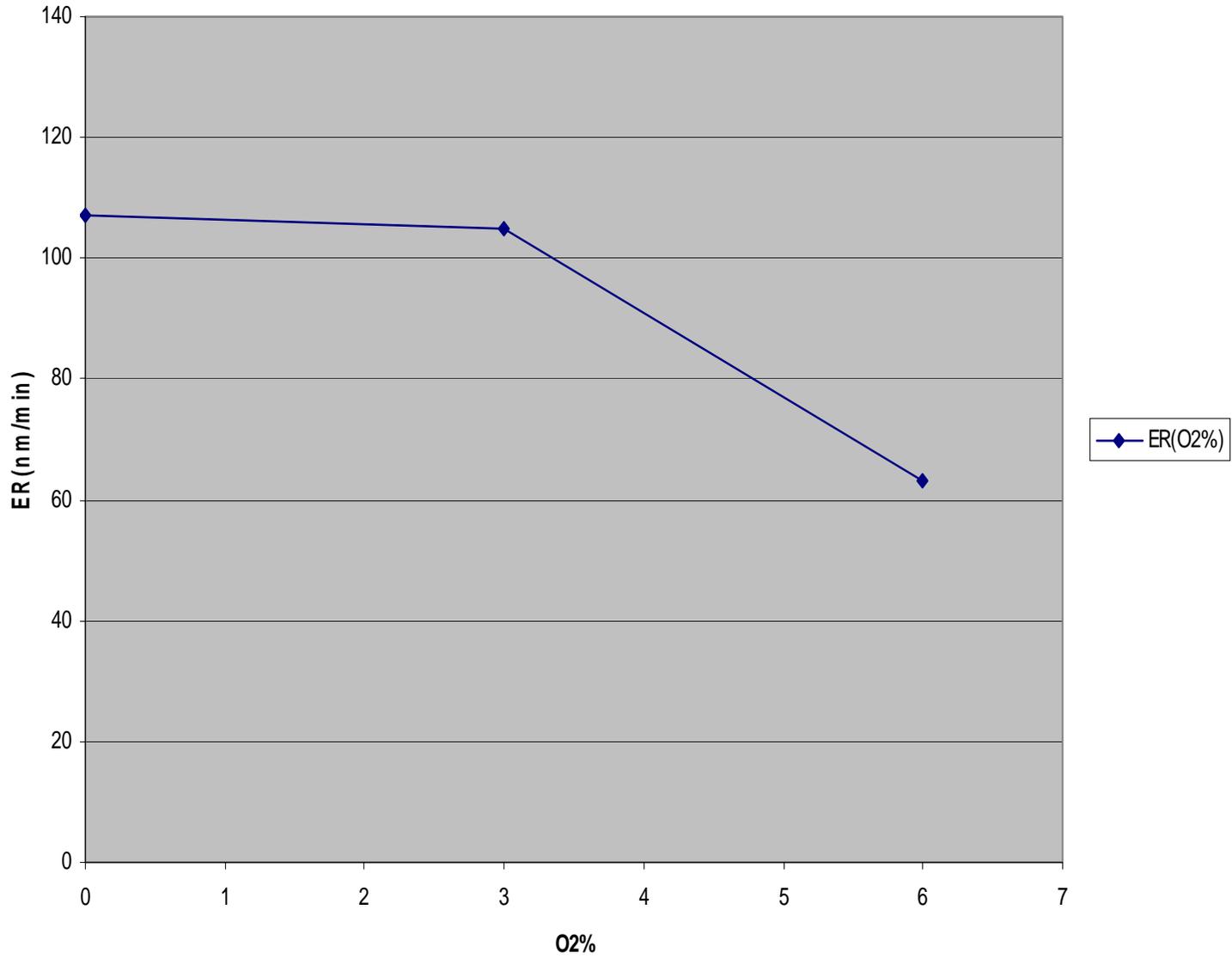
# POLY/S-XTAL ER(H2)



# O<sub>2</sub> addition to Cl<sub>2</sub> based Si etching

- Small (10%) amount of can increase selectivity to underlying oxide required for an overetch.
- Competitive oxidation of the Si surface plays an important role in ARDE and in the transition from RIE lag to inverse RIE lag without a significant change in sidewall profile.
- RIE lag is an issue for HAR structures leading to profile artifacts, such as trenching
- 10% oxygen can eliminate RIE lag with greater amounts inverting RIE lag
- The AR dependence in the presence of O<sub>2</sub> is dependent on oxygen atom flux to the bottom of a microstructure as its width is reduced.
- The large sticking coefficient of oxygen on resist and polysilicon sidewalls in addition to neutral shadowing further limits the incident flux.
- Presence of BCl<sub>3</sub> leads to competition between oxygen scavenging and oxidation.

ER(O2%)



S-OX(O2%)

