



**Figure 3.3** The inversion coefficient presented as a number line showing the regions and subregions of MOS inversion with corresponding effective gate–source voltage,  $V_{EFF} = V_{GS} - V_T$ . The effective gate–source voltage is for room temperature ( $T = 300$  K) and an average substrate factor of  $n = 1.4$ . It is higher than values shown for short-channel devices operating in strong inversion due to velocity saturation. Moderate inversion is increasingly important in modern, low-voltage processes because of lower allowable effective gate–source and drain–source saturation voltages

The value of  $V_{EFF}$  associated with a given  $IC$ , described later in Section 3.7.2, is approximately  $-4.5$ ,  $-2$ ,  $1.08$ ,  $6.24$ , and  $20 \cdot nU_T$  for  $IC = 0.01$ ,  $0.1$ ,  $1$ ,  $10$ , and  $100$ , respectively. Values given assume  $U_T = 25.9$  mV ( $T = 300$  K) and a constant value of  $n$  at  $1.4$ . Values given exclude the increase associated with velocity saturation present for short-channel devices at high levels of inversion.

The subregions of inversion are described below in terms of  $IC$  and the associated  $V_{EFF}$ . Additionally, a few comments about MOS transconductance efficiency,  $g_m/I_D$ , effective gate–source voltage,  $V_{EFF}$ , drain–source saturation voltage,  $V_{DS,sat}$ , intrinsic voltage gain, and intrinsic bandwidth are included. These aspects of MOS performance are developed in Sections 3.8.2, 3.7.2, 3.7.3, 3.8.5, and 3.9.6. Additionally, performance tradeoffs associated with the level of inversion are discussed in detail in Section 4.2.2 and summarized in Figure 4.1.

The subregions of MOS inversion shown in Figure 3.3 are:

- **Deep weak inversion ( $IC < 0.01$ ,  $V_{EFF} < -163$  mV).** Because the large device shape factor, channel width, and gate area required results in high gate capacitances, very low bandwidth, and potentially high DC leakage, operation here is not desirable. There is little increase in  $g_m/I_D$  or decrease in  $V_{DS,sat}$  here compared to the *high side of weak inversion*. Operation may be required here for very low drain currents.
- **High side of weak inversion ( $IC = 0.1$ ,  $V_{EFF} = -72$  mV).** This occurs at the boundary of moderate inversion. Operation here provides nearly the full  $g_m/I_D$  of *deep weak inversion*, low  $V_{EFF}$  and  $V_{DS,sat}$ , high gain, and low bandwidth, although improved bandwidth compared to *deep weak inversion*.
- **Weak-inversion side of moderate inversion ( $0.1 < IC < 1$ ,  $-72$  mV  $< V_{EFF} < 40$  mV).** This occurs between the boundary of weak inversion and the center of moderate inversion, with  $IC = 0.3$  corresponding to the geometric center between weak and moderate inversion. Operation here provides high  $g_m/I_D$ , low  $V_{EFF}$  and  $V_{DS,sat}$ , high gain, and improved bandwidth compared to the *weak-inversion side of moderate inversion*.
- **Center of moderate inversion ( $IC = 1$ ,  $V_{EFF} = 40$  mV).** Operation in the center of moderate inversion provides good  $g_m/I_D$ , low  $V_{EFF}$  and  $V_{DS,sat}$ , good gain, and modest bandwidth.
- **Strong-inversion side of moderate inversion ( $1 < IC < 10$ ,  $40$  mV  $< V_{EFF} < 225$  mV).** This occurs between the center of moderate inversion and the boundary or onset of strong inversion, with  $IC = 3$  corresponding to the geometric center between moderate and strong inversion. Operation here provides modest  $g_m/I_D$ , modestly increasing  $V_{EFF}$  and  $V_{DS,sat}$ , modest gain, and good bandwidth.