Computational Microelectronics L18

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Transient device simulation

Changes from DC

- Poisson equation
  - We don't have to change it. No time derivative term in it.

$$\nabla \cdot [\epsilon(\mathbf{r})\nabla\phi] + qp(\mathbf{r}) - qn(\mathbf{r}) + qN_{dop}^{+}(\mathbf{r}) = 0$$

- Continuity equations
  - We must consider the time derivative terms.

$$-q\frac{\partial n}{\partial t} + \nabla \cdot \mathbf{J}_n = 0$$

$$q\frac{\partial p}{\partial t} + \nabla \cdot \mathbf{J}_p = 0$$

Integrated form

- Integrated in the 1D space around x_i
  - Time derivative term is simply multiplied by Δx.

$$-q\frac{\partial n(x_i)}{\partial t}\Delta x + J_n(x_{i+0.5}) - J_n(x_{i-0.5}) = 0$$

  - With the backward Euler,

$$-q\frac{n(x_i) - n_{past}(x_i)}{\Delta t}\Delta x + J_n(x_{i+0.5}) - J_n(x_{i-0.5}) = 0$$

  - Therefore, we must memorize $n_{past}(x_i)$.

Jacobian

- It is noted that $n_{past}(x_i)$ is not a unknown variable.
  - It does not contribute to the Jacobian matrix.
  - The only change in the Jacobian matrix (Electron continuity equation)

$$\frac{\partial}{\partial n(x_i)}\left[-q\frac{n(x_i)-n_{past}(x_i)}{\Delta t}\Delta x\right] = -q\frac{\Delta x}{\Delta t}$$

  - It is corresponding to a diagonal component of the Jacobian matrix.

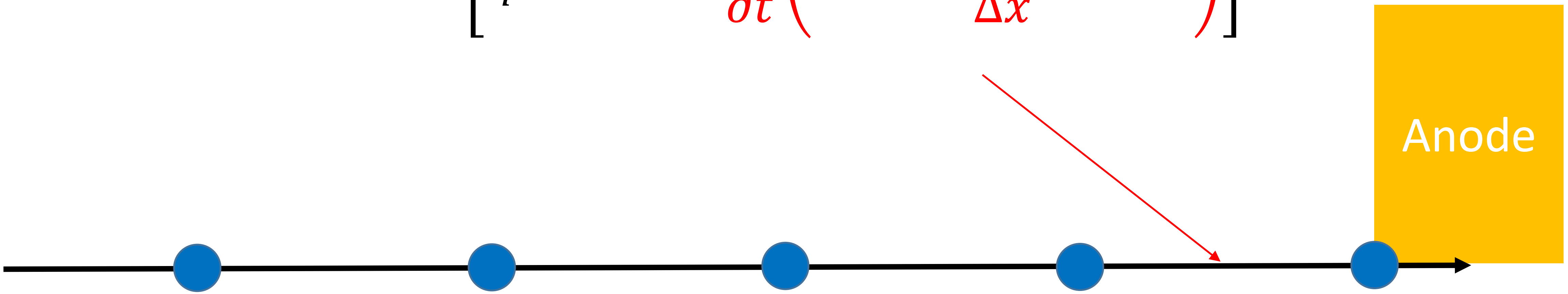
Displacement current

- In general,

$$I_{terminal} = -\int_{terminal\ area} \left(\mathbf{J}_p + \mathbf{J}_n + \frac{\partial \mathbf{D}}{\partial t} \right) \cdot d\mathbf{a}$$

- In a 1D structure, it is very simple.
  - Sum of current densities at the edge connected to the terminal

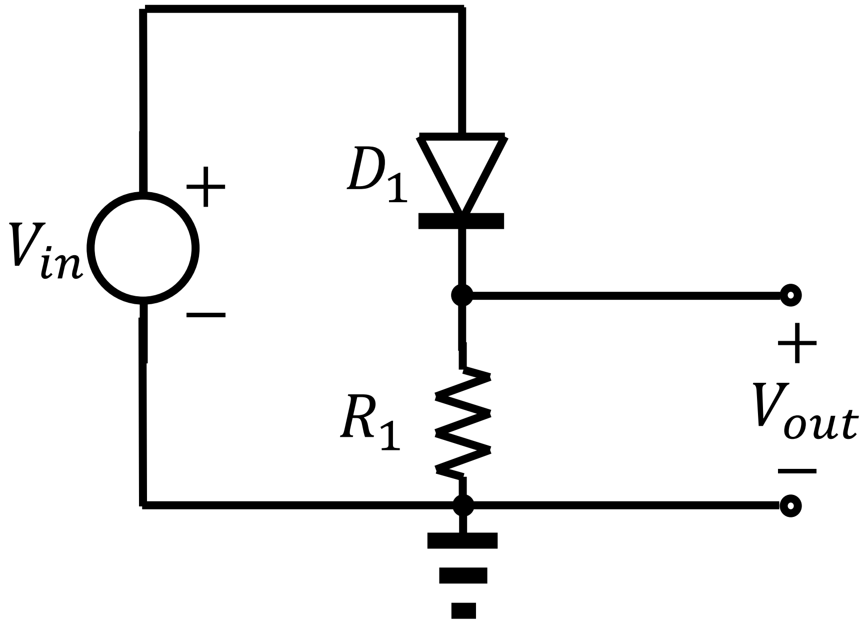
$$I_{anode} = -\left[J_p + J_n - \epsilon \frac{\partial}{\partial t} \left(\frac{\phi(x_N) - \phi(x_{N-1})}{\Delta x} \right) \right] A$$



Mixed-mode simulation

A simple rectifier

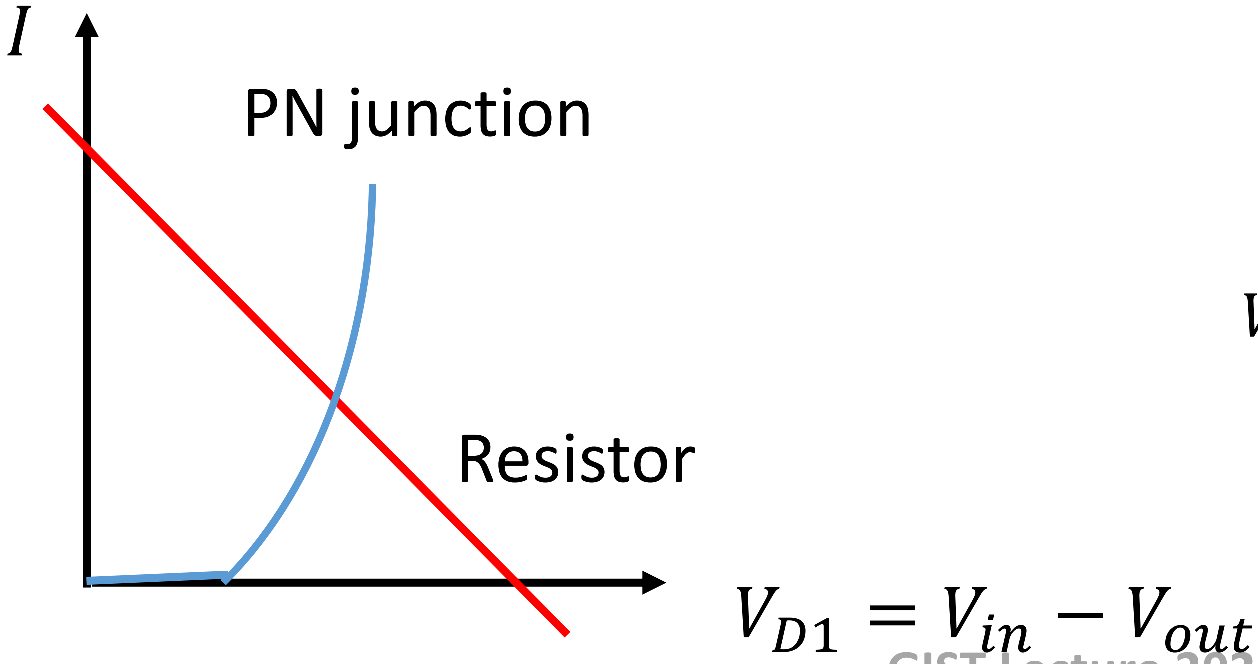
- We have made a device simulator.
- Can we simulate the following circuit?
  - Well, right now, it is not possible.

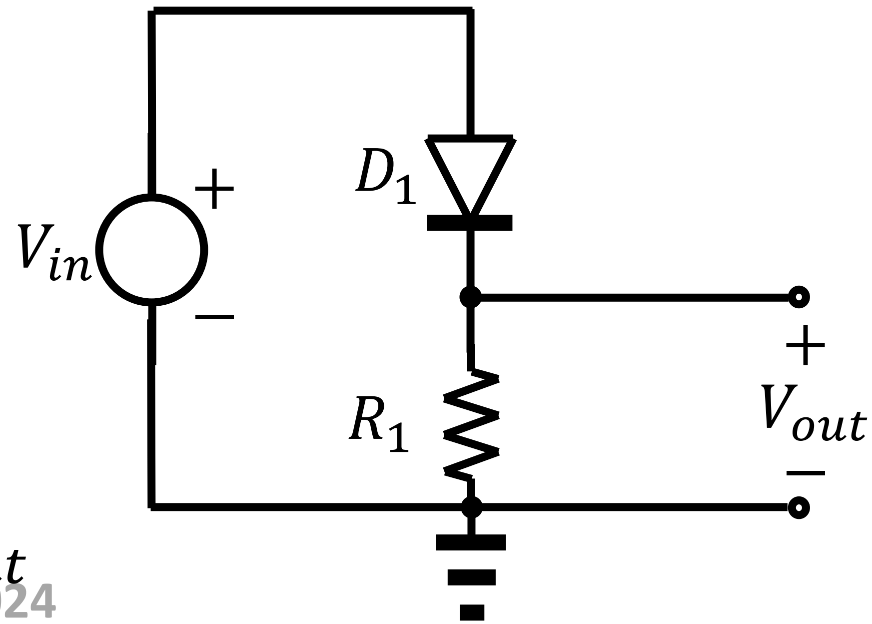


One remedy

- When we know the DC characteristics of the PN junction, $I_{D1}(V_{anode} - V_{cathode})$,
  - We may additionally solve the following equation:

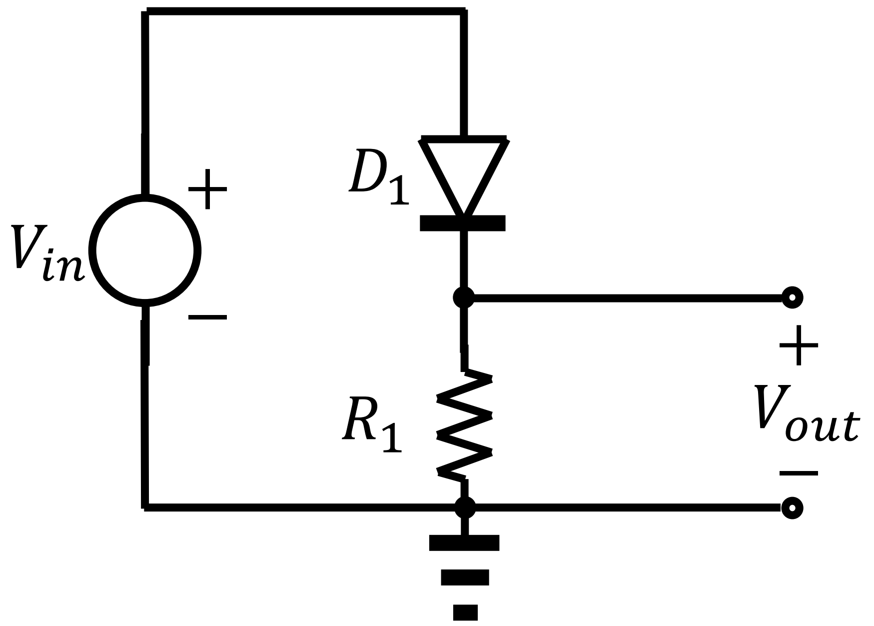
$$I_{D1}(V_{in} - V_{out}) = \frac{V_{out}}{R_1}$$





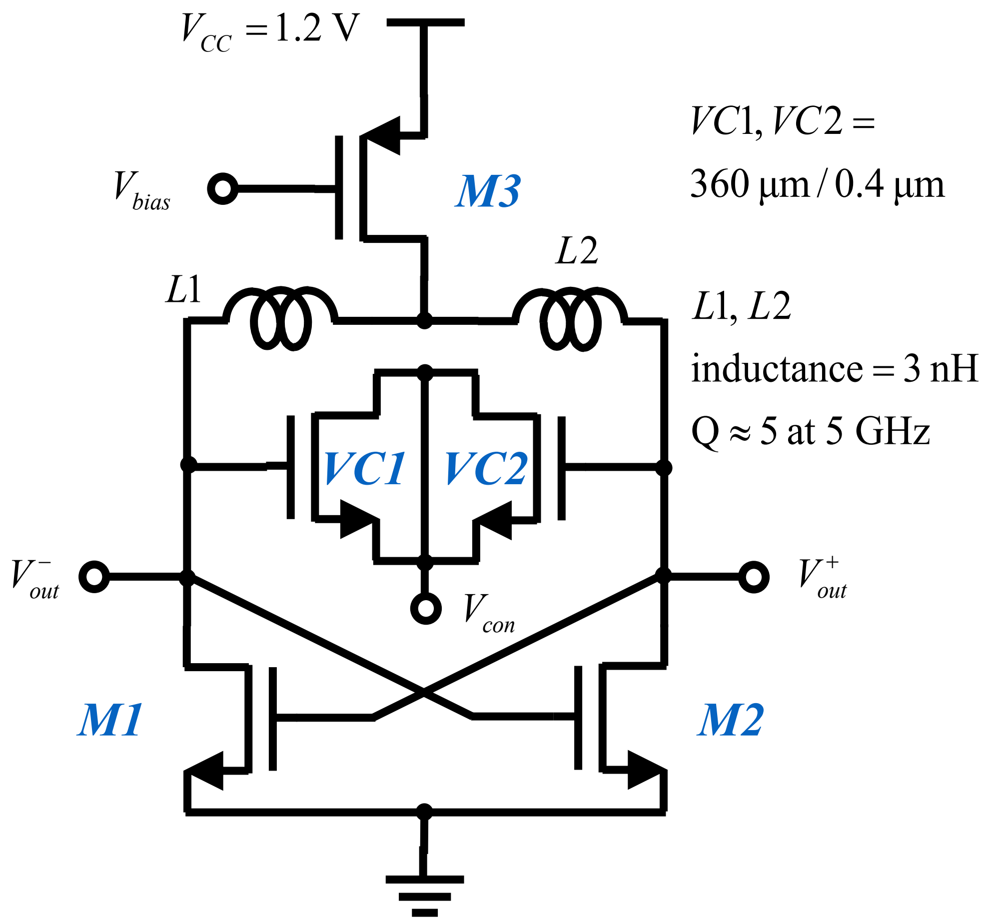
Mixed-mode simulation

- In the mixed-model simulation,
  - Not only semiconductor devices but also circuit elements are simulated together.
  - It couples the device simulator and the circuit simulator.



General implementation

- We must parse the netlist.
  - In this example,
  - Two NMOSFETs (M1 and M2)
  - Two MOS varactors (VC1 and VC2)
  - One PMOSFET (M3)
  - Two inductors (L1 and L2)

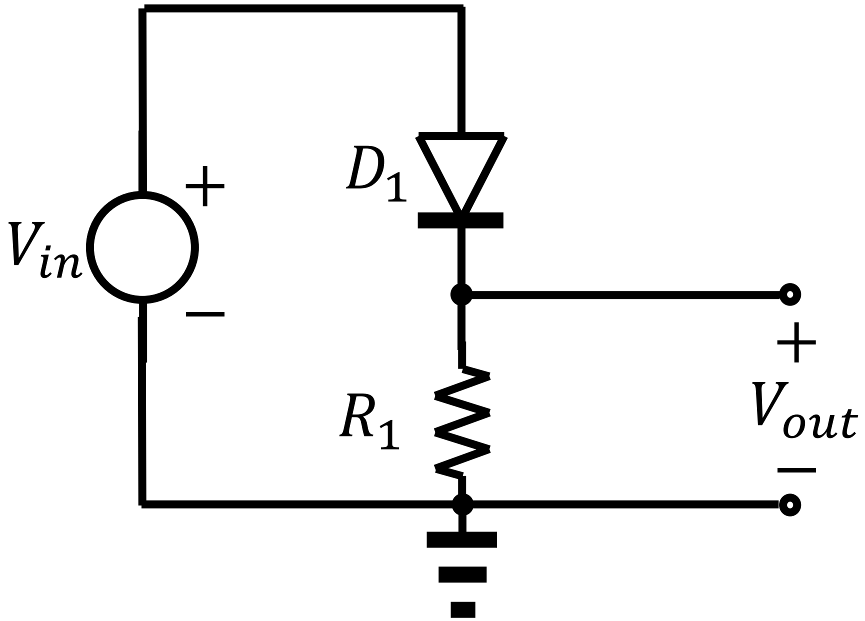


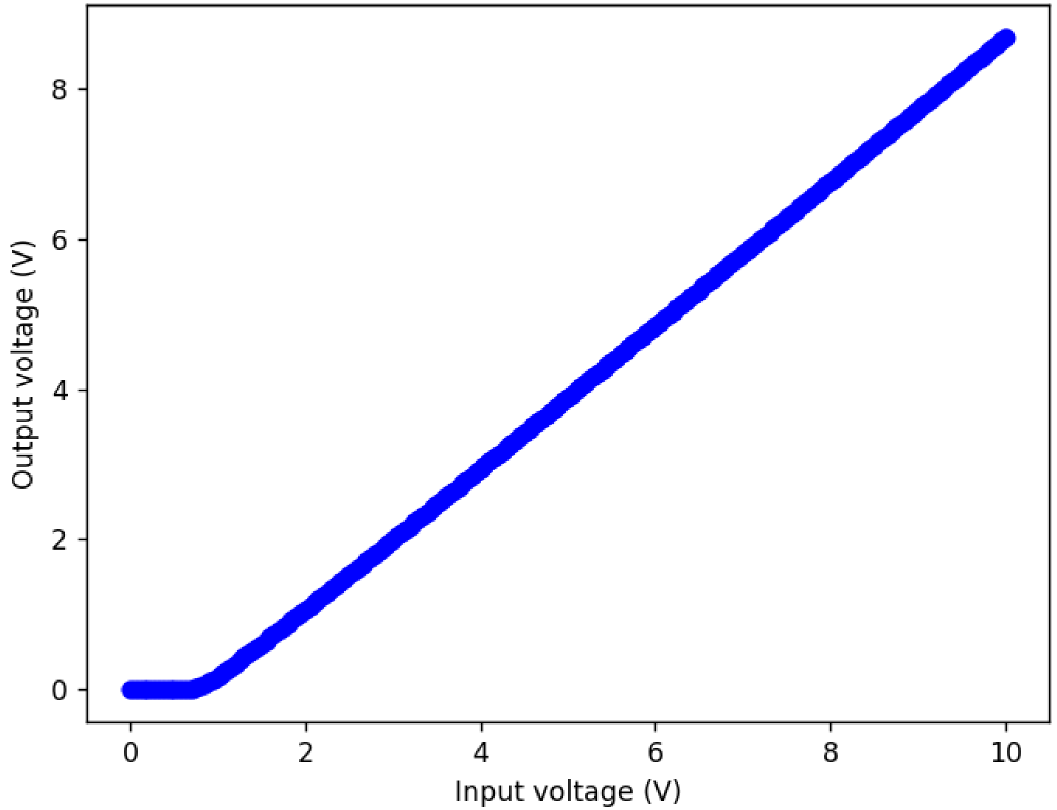
A resistor attached to a terminal

- Instead of the general implementation, consider a resistor, R_i, attached to the i-th terminal.
  - Its voltage is $V_{i,external}$.
  - There occurs a voltage drop due to the terminal current. Therefore, the actual voltage applied to the device becomes
  $$V_{i,internal} = V_{i,external} - I_i \times R_i$$
  - Just use $V_{i,internal}$ instead of $V_{i,external}$ for the boundary condition.
  - I_i and $V_{i,internal}$ should be included for better convergence behavior.

An example

- Consider a symmetric, abrupt PN junction. Its doping density is 10^{17} cm^{-3}. Assume that μ_n = 1417 cm^2/V sec and μ_p = 407.5 cm^2/V sec. The area is 1 μm^2. The resistor is 1 kΩ.
  - Increase the voltage up to 10 V.



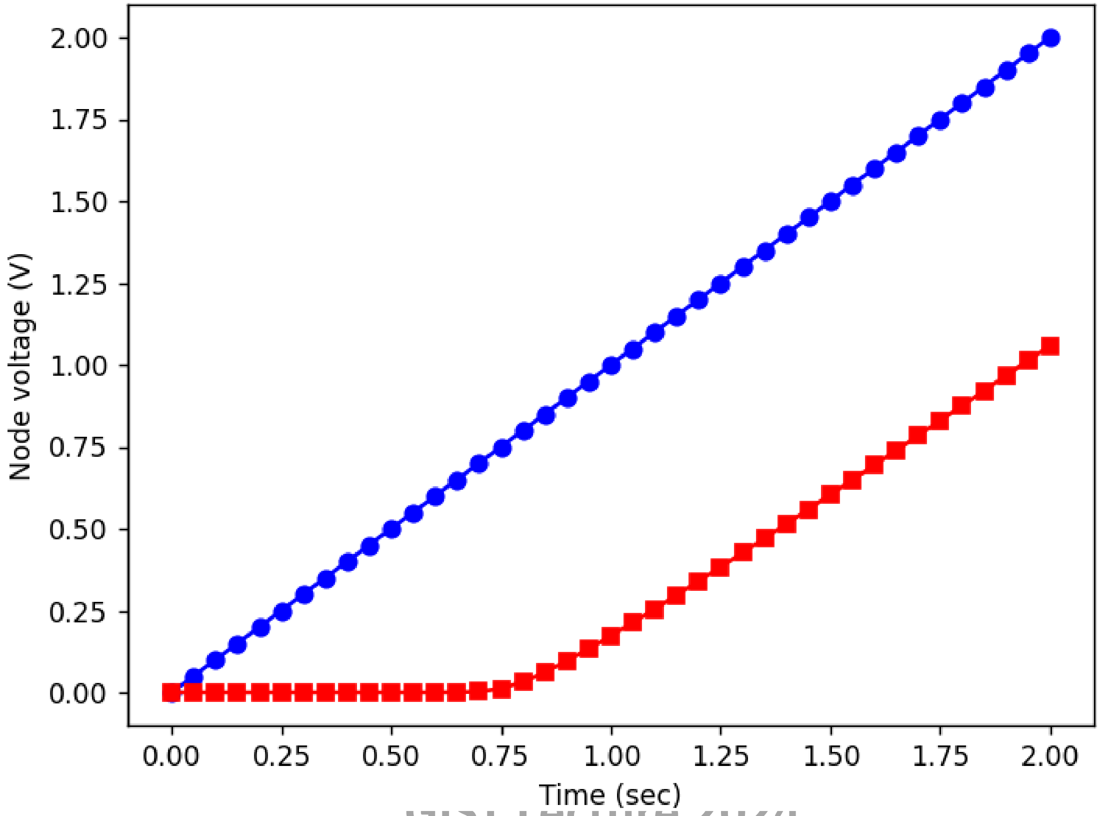


Convergence behavior

- When the Jacobian entries for the terminal current ($I_{cathode}$) are neglected,
  - We cannot get the converged solution at 0.8 V. (0.05 V spacing)
- When the Jacobian entries for the terminal current are neglected ($V_{cathode,internal} = -I_{cathode} \times R_{cathode}$),
  - We cannot get the convergence solution at 0.8 V. (0.05 V spacing)
- It is very important to consider $I_{cathode}$ and $V_{cathode,internal}$ accurately in the Jacobian matrix.

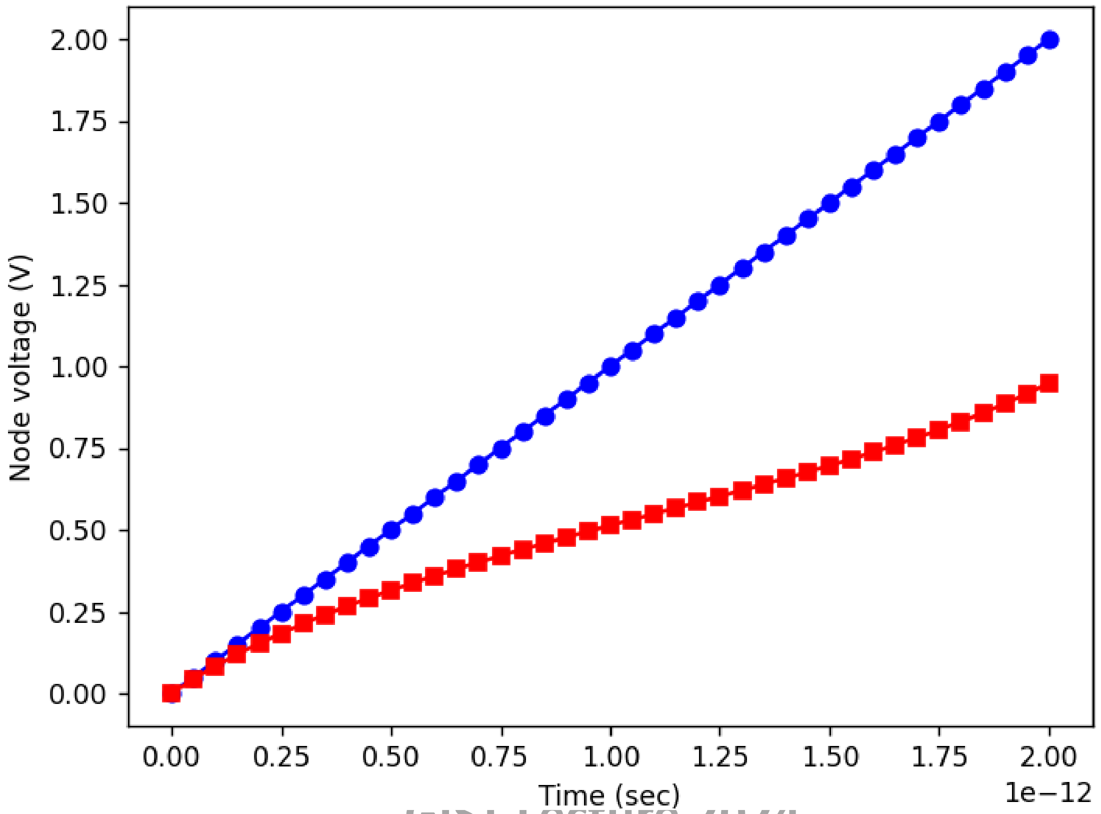
The same rectifier circuit

- The input voltage is increased up to 2 V.
  - The ramping rate is changed.
  - First, let's try 1 V/sec. (Extremely slow)



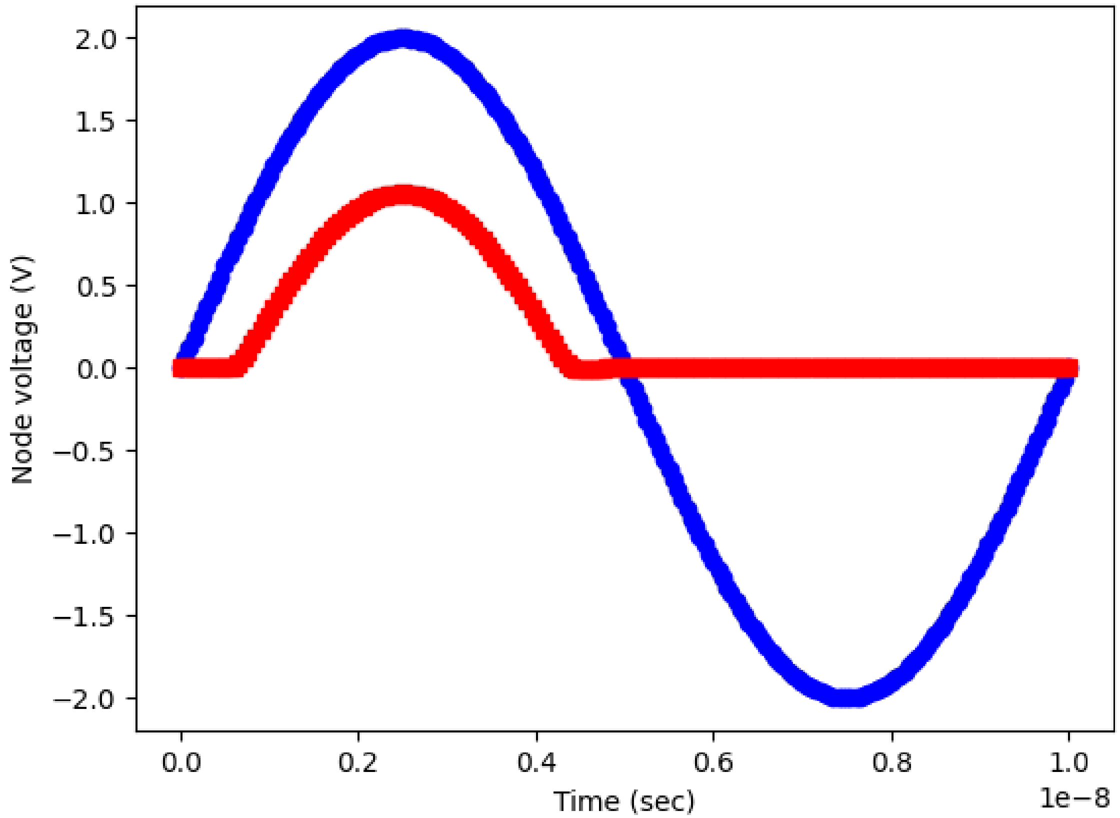
Much faster ramping

- The ramping rate is now 1 V/psec. (Extremely fast)
  - The PN junction cannot respond properly.



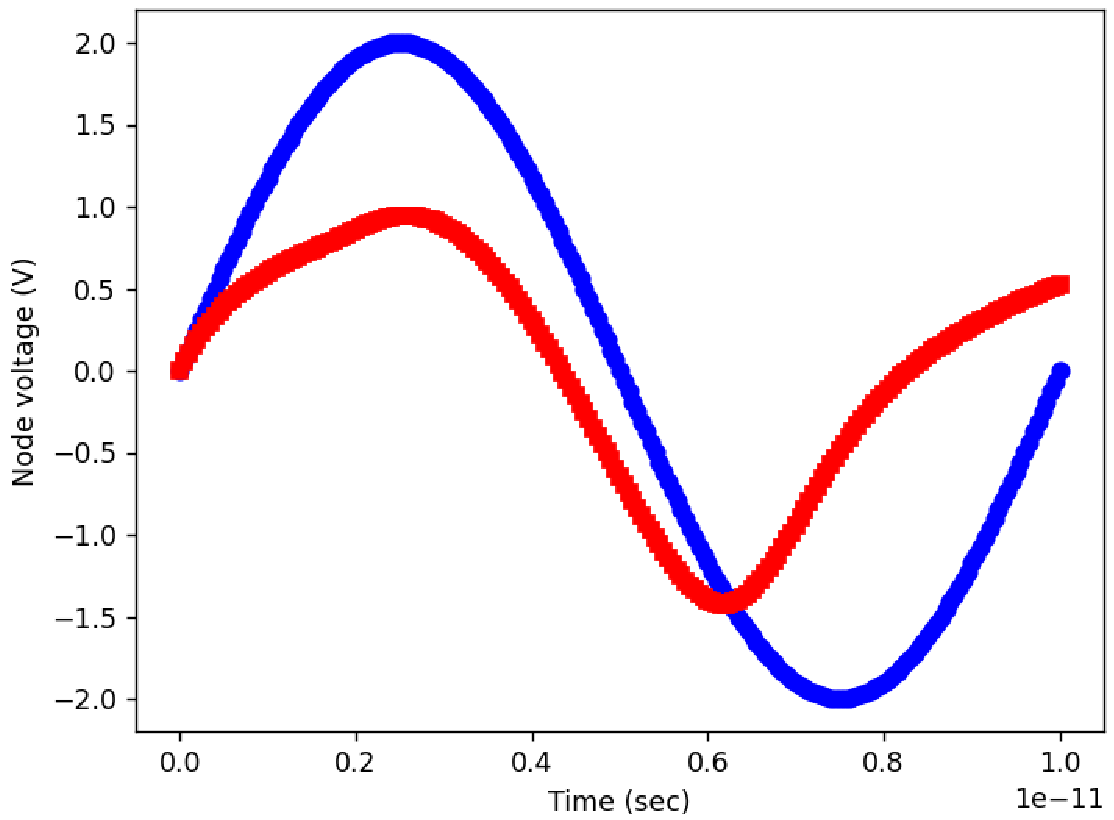
Sinusoidal signal

- We apply a sinusoidal signal whose amplitude is 2 V.
  - One period is divided into 200 intervals.
  - First, 100 MHz



Sinusoidal signal

- Once again, we try a much higher frequency, 100 GHz.
  - Its first period looks very different from 100 MHz.



Homework#18

- Due: AM08:00, November 21
- Problem#1
  - By implementing a transient DD solver, reproduce the results of the examples covered in class.

Thank you for your attention!