Neuromorphic engineering I

Lab 9: Silicon Neuron Circuits

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In this lab, we will test a circuit that generates action potentials (spikes) based on an integrate-and-fire model of a neuron spike initiation zone.

The objectives of this lab are:

1. to understand the spiking properties of I&F circuits.
2. to evaluate the effect of the I&F circuit's different bias parameters on its spiking behaviour.

1 Setup

2.1 Connect the device

In [1]:

```
# import the necessary libraries
import pyplane
import time
import numpy as np
import matplotlib.pyplot as plt
from scipy import interpolate
```

In [2]:

```
# create a Plane object and open the communication
if 'p' not in locals():
    p = pyplane.Plane()
    try:
        p.open('/dev/ttyACM0')
    except RuntimeError as e:
        del p
        print(e)
```

In [3]:

```
p.get_firmware_version()
```

Out[3]:

```
(1, 8, 4)
```

In [4]:

```
# Send a reset signal to the board, check if the LED blinks
p.reset(pyplane.ResetType.Soft)
time.sleep(0.5)
# NOTE: You must send this request events every time you do a reset operetion, otherwise t
# Because the class chip need to do handshake to get the communication correct.
p.request_events(1)
```

In [5]:

```
# Try to read something, make sure the chip responses
p.read_current(pyplane.AdcChannel.GO0_N)
```

Out[5]: 1.7724609335800778e-07

In [6]:
```
 # If any of the above steps fail, delete the object, close and halt, stop the server and
# please also say your board number: ttyACMx

# del p
```

2.2 Disable unused circuits

In [7]:
```
# disable synapses
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.LDS_VTAU_P, \
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I60pA, 0)])

p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.DPI_VTAU_P, \
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I60pA, 0)])

p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.DDI_VTAU_P, \
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I60pA, 0)])
```

In [8]:
```
# disable axon-hillock neuron
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.AHN_VPW_N, \
    pyplane.Coach.BiasType.P, \
    pyplane.Coach.BiasGenMasterCurrent.I60pA, 0)])
```

In [9]:
```
# disable thresholded neuron
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.ATN_VLEAK_N, \
    pyplane.Coach.BiasType.P, \
    pyplane.Coach.BiasGenMasterCurrent.I60pA, 0)])

p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.ATN_VDC_P, \
    pyplane.Coach.BiasType.P, \
    pyplane.Coach.BiasGenMasterCurrent.I60pA, 0)])

p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.ATN_VGAIN_N, \
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I60pA, 0)])

p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.ATN_VSPKTHR_P, \
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I60pA, 0)])
```

In [10]:
```
# disable sigma-delta neuron
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.ASN_VLEAK_N, \
    pyplane.Coach.BiasType.P, \
    pyplane.Coach.BiasGenMasterCurrent.I60pA, 0)])
```

```
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.ASN_VDC_P, \
    pyplane.Coach.BiasType.P, \
    pyplane.Coach.BiasGenMasterCurrent.I60pA, 0)])

p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.ASN_VGAIN_N, \
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I60pA, 0)])
```

In [11]:

```
# disable exp neuron
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.ACN_VLEAK_N, \
    pyplane.Coach.BiasType.P, \
    pyplane.Coach.BiasGenMasterCurrent.I60pA, 0)])

p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.ACN_VGAIN_N, \
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I60pA, 0)])

p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.ACN_VDC_P, \
    pyplane.Coach.BiasType.P, \
    pyplane.Coach.BiasGenMasterCurrent.I60pA, 0)])

p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.ACN_VREFR_N, \
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I240nA, 255)])
```

In [12]:

```
# disable hodgekin-huxley neuron
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.HHN_VBUF_N, \
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I60pA, 0)])

p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.HHN_VCABUF_N, \
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I60pA, 0)])

p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.HHN_VDC_P, \
    pyplane.Coach.BiasType.P, \
    pyplane.Coach.BiasGenMasterCurrent.I60pA, 0)])

p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.HHN_VELEAK_N, \
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I60pA, 0)])
```

In [13]:

```
# disable DVS pixels
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.DVS_DIFF_N, \
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I60pA, 0)])

p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.DVS_CAS_N, \
    pyplane.Coach.BiasType.N, \
```

```
    pyplane.Coach.BiasGenMasterCurrent.I60pA, 0)])

p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.DVS_ON_N, \
    pyplane.Coach.BiasType.P, \
    pyplane.Coach.BiasGenMasterCurrent.I60pA, 0)])

p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.DVS_OFF_N, \
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I60pA, 0)])

p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.DVS_SF_P, \
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I60pA, 0)])

p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.DVS_PR_P, \
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I60pA, 0)])

p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.DVS_REFR_P, \
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I60pA, 0)])
```

2.3 Chip configurations

In [14]:

```
# select lines and neuron latches
p.send_coach_events([pyplane.Coach.generate_aerc_event(
    pyplane.pyplane.Coach.CurrentOutputSelect.SelectLine6,
    pyplane.Coach.VoltageOutputSelect.SelectLine2,
    pyplane.Coach.VoltageInputSelect.NoneSelected,
    pyplane.Coach.SynapseSelect.NoneSelected,320)])
```

In [15]:

```
# setup output rail-to-rail buffer
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.RR_BIAS_P, \
    pyplane.Coach.BiasType.P, \
    pyplane.Coach.BiasGenMasterCurrent.I240nA, 255)])
```

In [16]:

```
# set up sampling mode
# p.set_sampling_mode(pyplane.SamplingMode.Fast)
# p.set_fast_sampling_adcs([10])
```

2.4 BiasGen

In a simplified form, the output of a branch of the BiasGen will be the gate voltage V_b for the bias current I_b, and if the current mirror has a ratio of w and the bias transistor operates in subthreshold-saturation:

$$I_b = w \frac{BG_{fine}}{256} I_{BG_{master}} \tag{1}$$

Where $I_{BG_{master}}$ is the `BiasGenMasterCurrent` $\in \{60\ \mathrm{pA}, 460\ \mathrm{pA}, 3.8\ \mathrm{nA}, 30\ \mathrm{nA}, 240\ \mathrm{nA}\}$, BG_{fine} is the integer fine value $\in [0, 256)$

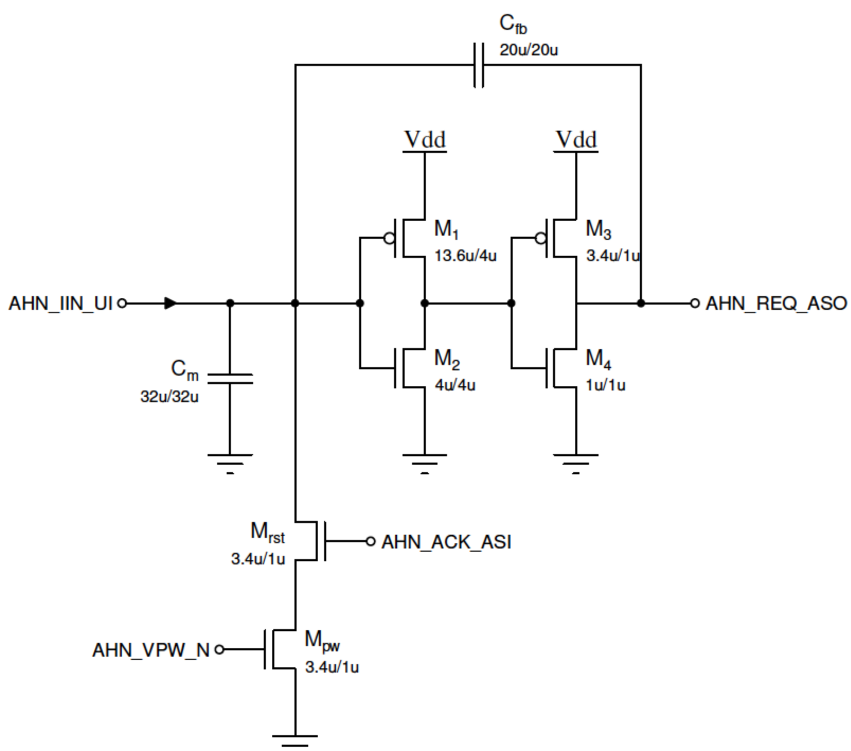
To set a bias, use the function similar to the following:

```
p.send_coach_event(pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.BIAS_NAME, \
    pyplane.Coach.BiasType.BIAS_TYPE, \
    pyplane.Coach.BiasGenMasterCurrent.MASTER_CURRENT, FINE_VALUE))
```

You may have noticed that there are some biases that are not used to directly generate a current, but rather what matters is the voltage, e.g. V_{gain}, V_{ex} and V_{inh} in our HWTA circuit. Even though they may have a `BIAS_NAME` ending with `_N` or `_P` it only indicates that they are connected to the gate of an N- or a P-FET, but the `BIAS_TYPE` parameter can be both `_N` or `_P`. For example, setting a `_N` bias to `BIAS_TYPE = P` will only make this voltage very close to GND, which *is* sometimes the designed use case.

2 Axon-Hillock neuron

The axon-hillock neuron has a constant current input `AHN_IIN_UI` which is about pA (exact value not known), and the voltage on capacitor C_m is output to **ADC[11]**.



2.1 Basic measurement

- Tune `AHN_VPW_N` bias so that the output waveform is more or less symmetric.

In [18]:
```
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.AHN_VPW_N,\
    pyplane.Coach.BiasType.N,\
    pyplane.Coach.BiasGenMasterCurrent.I60pA,2)])
```

- Data aquisition

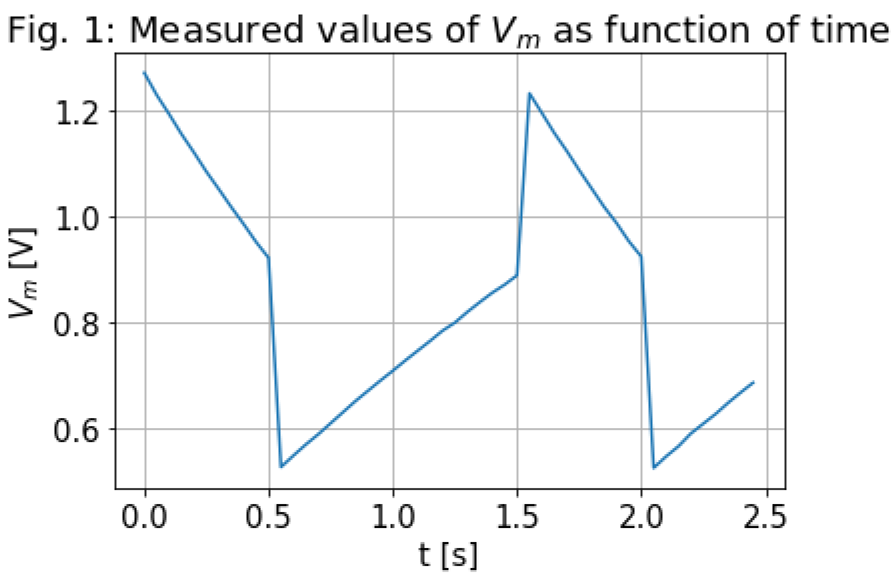
In [19]:
```
N_samples = 50
```

```
dT = 0.05

t = np.arange(N_samples)*dT
v = np.zeros(N_samples)  # v_Cm

for i in range(N_samples):
    v[i] = p.read_voltage(pyplane.AdcChannel.AOUT11)
    time.sleep(dT)
```

- Plot data

In [24]:

```
import matplotlib.pyplot as plt
import numpy as np
plt.rcParams.update({'font.size': 15})


t,v = np.loadtxt('data/data_ex_2_1.csv',delimiter=',')

plt.plot(t,v)

plt.xlabel('t [s]')
plt.ylabel('$V_{m}$ [V]')
plt.title('Fig. 1: Measured values of $V_{m}$ as function of time')

plt.grid()
plt.show()
```



- Save data

In [22]:

```
np.savetxt('data/data_ex_2_1.csv',[t,v] , delimiter=',')
```

2.2 Different pulse widths

Now try two more `AHN_VPW_N` values and compare the three curves in the same plot.

In [25]:

```
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.AHN_VPW_N,\
    pyplane.Coach.BiasType.N,\
    pyplane.Coach.BiasGenMasterCurrent.I60pA,1)])
```

In [26]:

```
N_samples = 50
dT = 0.05

t = np.arange(N_samples)*dT
v = np.zeros(N_samples)  # v_Cm

for i in range(N_samples):
    v[i] = p.read_voltage(pyplane.AdcChannel.AOUT11)
    time.sleep(dT)
```

In [27]:

```
np.savetxt('data/data_ex_2_2_smaller.csv',[t,v] , delimiter=',')
```

In [32]:

```
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.AHN_VPW_N,\
    pyplane.Coach.BiasType.N,\
    pyplane.Coach.BiasGenMasterCurrent.I60pA,3)])
```

In [33]:

```
N_samples = 50
dT = 0.05

t = np.arange(N_samples)*dT
v = np.zeros(N_samples)  # v_Cm

for i in range(N_samples):
    v[i] = p.read_voltage(pyplane.AdcChannel.AOUT11)
    time.sleep(dT)
```

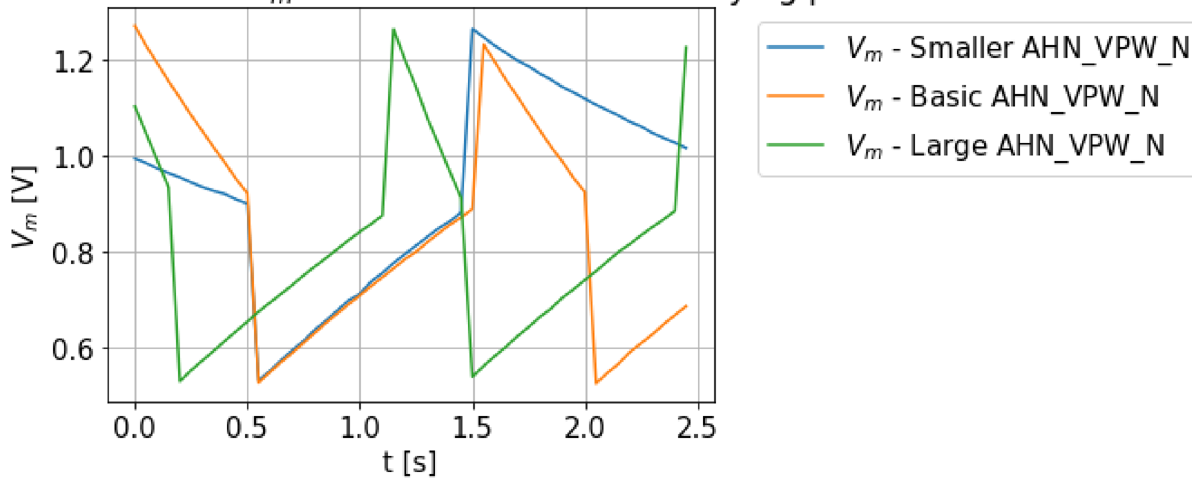
In [34]:

```
np.savetxt('data/data_ex_2_2_bigger.csv',[t,v] , delimiter=',')
```

In [35]:

```
import matplotlib.pyplot as plt
import numpy as np
plt.rcParams.update({'font.size': 15})

t,v = np.loadtxt('data/data_ex_2_1.csv',delimiter=',')
_,v_smaller = np.loadtxt('data/data_ex_2_2_smaller.csv',delimiter=',')
_,v_bigger = np.loadtxt('data/data_ex_2_2_bigger.csv',delimiter=',')

plt.plot(t,v_smaller,t,v,t,v_bigger)
plt.legend(['$V_{m}$ - Smaller AHN_VPW_N','$V_{m}$ - Basic AHN_VPW_N','$V_{m}$ - Large AHN

plt.xlabel('t [s]')
plt.ylabel('$V_{m}$ [V]')
plt.title('Fig. 2: Measured values of $V_{m}$ as function of time for varying pulse widths

plt.grid()
plt.show()
```

Fig. 2: Measured values of V_m as function of time for varying pulse widths



2.3 Switch off the circuit

- To avoid the output events interfering with other circuits, we set `AHN_VPW_N` to maximum again.

In [36]:

```
# disable axon-hillock neuron
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.AHN_VPW_N, \
    pyplane.Coach.BiasType.P, \
    pyplane.Coach.BiasGenMasterCurrent.I60pA, 0)])
```

3 Basic behavoir of classic I&F neuron

The **ADEXIF** (Adaptive Exponential Integrate & Fire) **classic neuron** comprises four major functional blocks: a leaky DPI (=integrate), starved-inverter (=fire), refractory period (=reset) and adaptation block. The adaptation block receives the the spike pulse of the neuron itself through a pulse extender circuit.

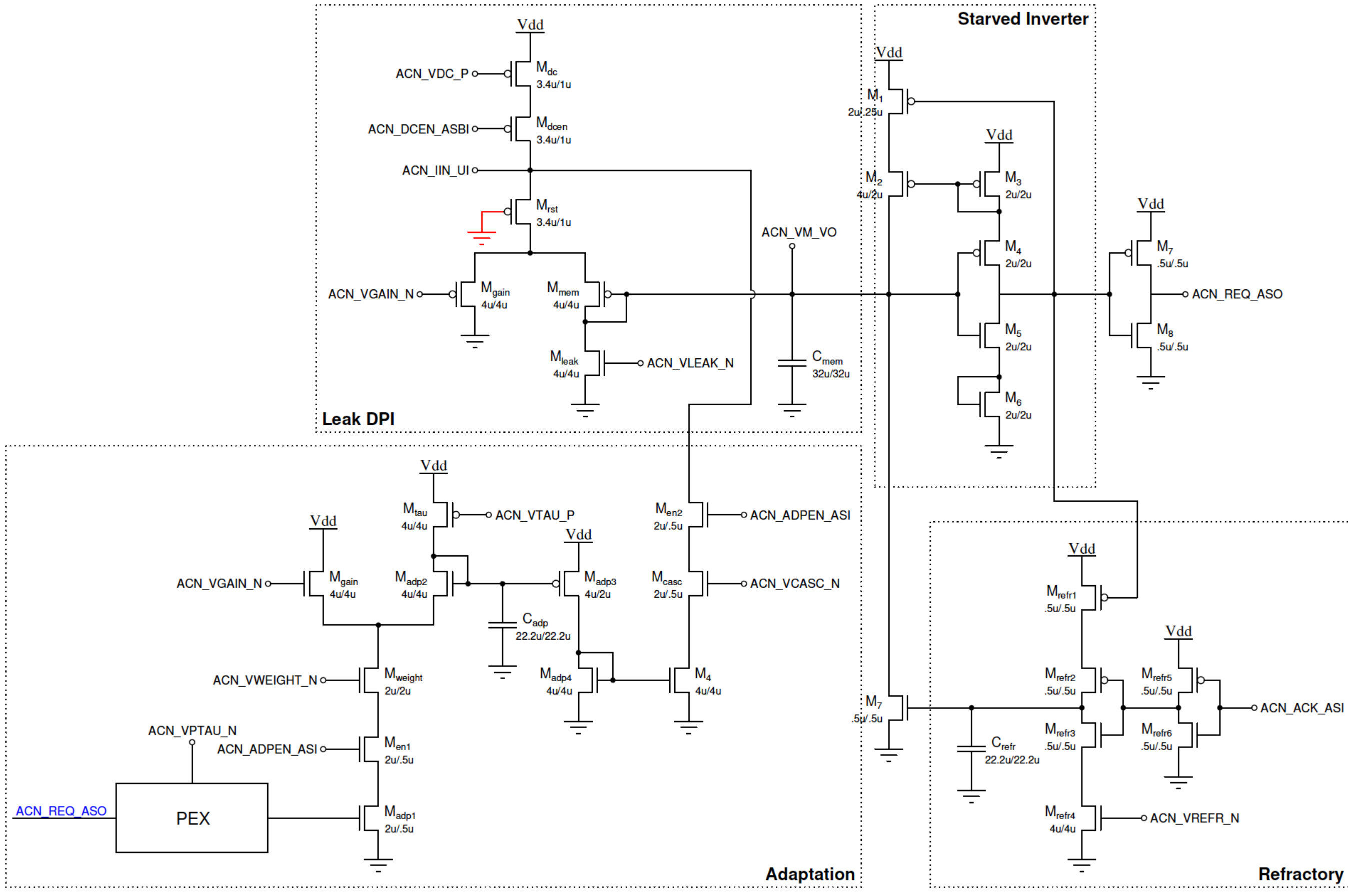
The circuit receives an input current I_{in} (typically the output of a synapse, I_{syn}) and outputs an AER event.

The membrane voltage V_{mem} is provided to observe the internal neuron state at **ADC[10]**.

The neuron circuit has 4 basic biases: V_{dc}, V_{gain}, V_{leak} and V_{refr}. The adaptation block has 5 more biases: $V_{adpgain}$, $V_{adpweight}$, V_{adptau}, $V_{adpcasc}$ & $V_{adpptau}$ (for the pulse extender).

There are two digital control bits: V_{adpen} to enable/disable adaptation, and V_{dcen} to disable/enable the V_{dc} bias input.

C_m sizing was chosen for a capacitance value of 2 pF, while C_{refr} and C_{adp} were chosen for a value of 1 pF.



3.1 Basic measurement

- Tune the biases such that the neuron fires at about 20 Hz.

In [53]:

```
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.ACN_VLEAK_N,\
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I60pA, 2)])

p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.ACN_VGAIN_N,\
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I60pA, 6)])

p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.ACN_VDC_P,\
    pyplane.Coach.BiasType.P, \
    pyplane.Coach.BiasGenMasterCurrent.I30nA, 10)])

p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.ACN_VREFR_N,\
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I30nA, 10)]) #change refractory period
```

- read data

In [65]:

```
timestep = 0.00025
vm1 = p.acquire_transient_response(pyplane.DacChannel.DAC1, pyplane.AdcChannel.AOUT10, 0.0
t = np.arange(len(vm1))*timestep
```

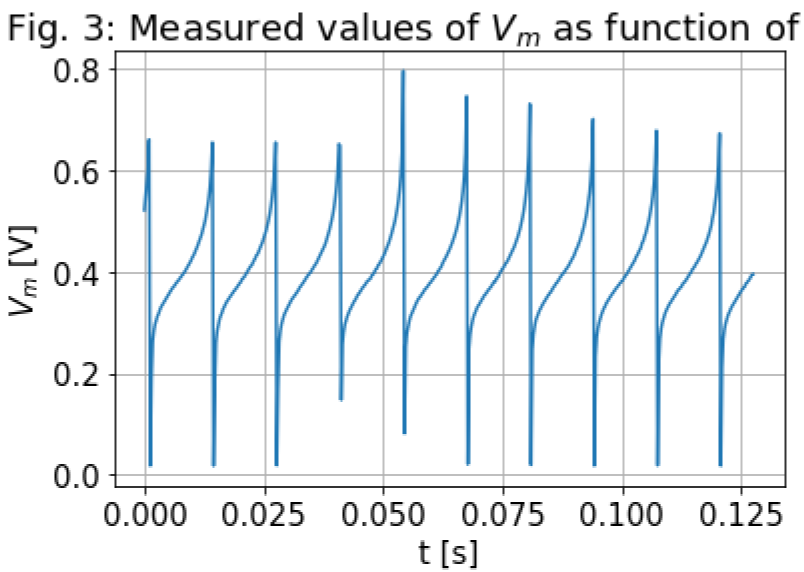
In [66]:

```
np.savetxt('data/data_ex_3_1.csv', [t, vm1], delimiter=',')
```

- Plot data

In [68]:

```
t, vm1 = np.loadtxt('data/data_ex_3_1.csv',delimiter=',')
plt.plot(t, vm1)
plt.xlabel('t [s]')
plt.ylabel('$V_{m}$ [V]')
plt.title('Fig. 3: Measured values of $V_{m}$ as function of time')

plt.grid()
plt.show()
```



> We didn't set the frequency to 20 Hz because the unit of the function has some problems, according to the TA.

3.2 Refractory period

Repeat 3.1 with two other refractory period biases and compare.

In [17]:

```
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.ACN_VLEAK_N,\
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I60pA, 2)])

p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.ACN_VGAIN_N,\
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I60pA, 6)])

p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.ACN_VDC_P,\
    pyplane.Coach.BiasType.P, \
    pyplane.Coach.BiasGenMasterCurrent.I30nA, 32)])

p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.ACN_VREFR_N,\
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I30nA, 10)]) #change refractory period
```

- read data

In [18]:

```
vm1 = p.acquire_transient_response(pyplane.DacChannel.DAC1, pyplane.AdcChannel.AOUT10, 0.0
np.savetxt('data/data_ex_3_2_base.csv', vm1, delimiter=',')
```

In [44]:

```
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.ACN_VLEAK_N,\
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I60pA, 2)])

p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.ACN_VGAIN_N,\
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I60pA, 6)])

p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.ACN_VDC_P,\
    pyplane.Coach.BiasType.P, \
    pyplane.Coach.BiasGenMasterCurrent.I30nA, 32)])

p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.ACN_VREFR_N,\
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I3_8nA, 1)]) #change refractory period
```

- read data

In [45]:

```
vm2 = p.acquire_transient_response(pyplane.DacChannel.DAC1, pyplane.AdcChannel.AOUT10, 0.0
np.savetxt('data/data_ex_3_2_smaller.csv', vm2, delimiter=',')
```

In [46]:

```
p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.ACN_VLEAK_N,\
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I60pA, 2)])

p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.ACN_VGAIN_N,\
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I60pA, 6)])

p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.ACN_VDC_P,\
    pyplane.Coach.BiasType.P, \
    pyplane.Coach.BiasGenMasterCurrent.I30nA, 32)])

p.send_coach_events([pyplane.Coach.generate_biasgen_event(\
    pyplane.Coach.BiasAddress.ACN_VREFR_N,\
    pyplane.Coach.BiasType.N, \
    pyplane.Coach.BiasGenMasterCurrent.I460pA, 20)]) #change refractory period
```

- read data

In [47]:

```
vm3 = p.acquire_transient_response(pyplane.DacChannel.DAC1, pyplane.AdcChannel.AOUT10, 0.0
np.savetxt('data/data_ex_3_2_bigger.csv', vm3, delimiter=',')
```

In [70]:

```
import matplotlib.pyplot as plt
```

```
import numpy as np
plt.rcParams.update({'font.size': 15})

t, _ = np.loadtxt('data/data_ex_3_1.csv', delimiter=',')
vm1 = np.loadtxt('data/data_ex_3_2_base.csv',delimiter=',')
vm2 = np.loadtxt('data/data_ex_3_2_smaller.csv',delimiter=',')
vm3 = np.loadtxt('data/data_ex_3_2_bigger.csv',delimiter=',')
plt.plot(t, vm1)
plt.title('Fig. 4: Measured values of $V_{m}$ as function of time for basic ACN_VREFR_N')
plt.xlabel('t [s]')
plt.ylabel('$V_{m}$ [V]')
plt.show()

plt.plot(t, vm2)
plt.title('Fig. 5: Measured values of $V_{m}$ as function of time for smaller ACN_VREFR_N'
plt.xlabel('t [s]')
plt.ylabel('$V_{m}$ [V]')
plt.grid()
plt.show()

plt.plot(t, vm3)
plt.title('Fig. 6: Measured values of $V_{m}$ as function of time for bigger ACN_VREFR_N')
plt.xlabel('t [s]')
plt.ylabel('$V_{m}$ [V]')
plt.grid()
plt.show()
```

Fig. 4: Measured values of V_m as function of time for basic ACN_VREFR_N

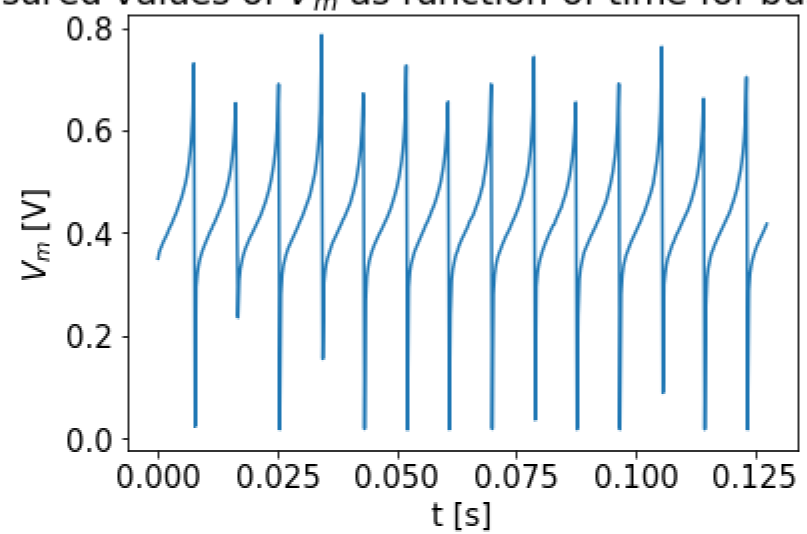


Fig. 5: Measured values of V_m as function of time for smaller ACN_VREFR_N

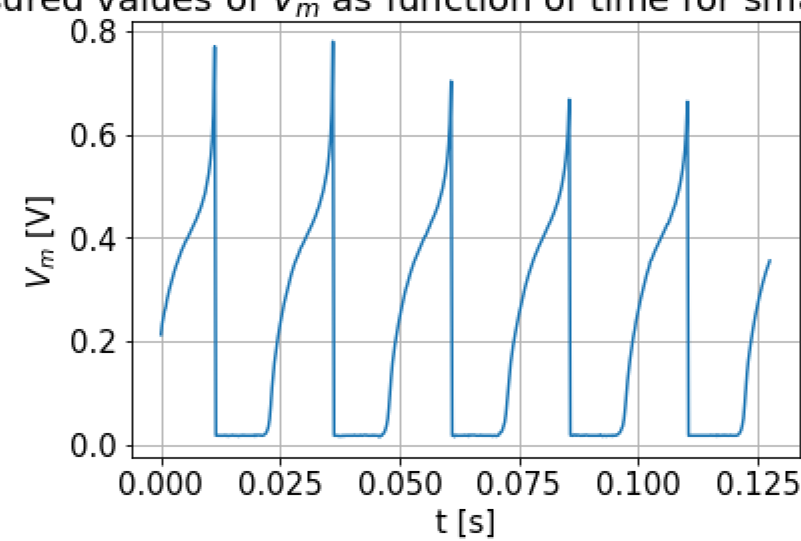


Fig. 6: Measured values of V_m as function of time for bigger ACN_VREFR_N