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COMMUNICATIONS

FLIP–FLOP SENSOR CONTROLLED BY FAST–RISE CONTROL PULSE

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The paper deals with dynamic the properties of a flip-flop sensor. Special attention will be paid to the condition of control by the fast-rise segment of the control pulse and to the derivation of the equivalent voltage. The results of theoretical considerations are verified by simulations using SPICE. To the best of author's knowledge, no publication dealing with derivation of a formula for the equivalent voltage of a flip-flop sensor controlled by a fast-rise control pulse has been reported.

Keywords: Flip-flop sensor, equivalent voltage, control pulse, non-electrical quantity, measurement.

1 INTRODUCTION

The flip-flop sensor is part of a class of silicon sensors with a digital output. The idea originated from the magnetic research area. A magnetic dipole in a material with a uniaxial anisotropic characteristic has two stable states: it aligns itself along one of the two directions of the axis. A magnetic sensor could be realized by setting the dipole in a position perpendicular to the axis, so that the dipole could be set free. The dipole would then go to one of the two stable states. Which one of the two stable states would be the final stable state of the dipole, depends on any perturbations present, such as a magnetic field. By designing the dipole system in such a way that its final stable state is sensitive to the magnetic field, and by detecting the final stable of the dipole, a magnetic field sensor could be constructed.

This idea is based on the deliverance of systems with stable states into an unstable state. It can be applied to any system or device with stable states. The electronic flip-flop is such a system. A flip-flop is depicted in Fig. 1. It has two stable states, namely the "one" and the "zero" state. The key element of a flip-flop sensor is the switching circuit or the so-called elementary memory. It differs from the conventional elementary memory by its method of control. The control pulses are not applied to the base or gates of the switching circuit but the circuit is repeatedly connected to an ideal source of voltage or current. To be able to quantify the corresponding non-electrical signal, it is advantageous to use sensor elements in building the circuit. Instead of conventional load resistors it is possible to use *eg* piezoresistors, photoresistors, magnetoresistors, *etc.* A similar situation arises in the case of transistors and inverters. It is better if they are phototransistors, magnetoresistors or transistors with multiple collectors, which can be used in the circuit for the measurement of the magnetic field. For the quantification of the strain it is possible to use also transistors with a piezoresistive channel. By using Ion Sensitive FET transistors it is possible to measure the pH of liquid media or to determine gas concentrations. If needed, however, it is not necessary to stick to the principle that the elements in Fig. 1 should be sensometric. Sensometric elements can be connected to the circuit externally. These can be sensor bridges as well as active thermocouples, Hall probes, *etc.*

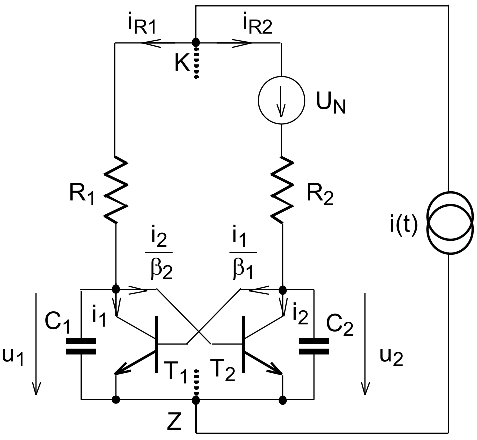

Fig. 1. Flip-flop sensor. Capacitances C_1 and C_2 represent parasitic capacitances of the transistors T_1, T_2.

But whichever of the above variants we choose, we always have to stick to the principle that the measured non-electrical quantity will break the value symmetry of the inverters relative to the morphological symmetry axis passing through points **K** and **Z**. If, for example, identical phototransistors are used for the illumination measurement, then the window of one of the bases is covered with an aluminium foil, which is done through a suitable technological process at the time of manufacture. Also in the strain measurement — if piezoresistors are used instead of load resistors, they must be orthogonally oriented on the chip so that when the chip is deformed one

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of the resistors is strained longitudinally and the other transversally so that the value symmetry is broken during the strain.

Through the action of the measured non-electrical quantity the originally symmetrical transfer characteristics of the first inverter $u_1(u_2)$ and the second inverter $u_2(u_1)$ will be changed into asymmetrical ones. However, it can be compensated by a voltage $U_N = U_{NE}$ in such a way that by repeated connection to a source $i(t)$ the 50 % state [1] is restored.

2 PHASE DESCRIPTION

The flip-flop sensor can be described by the system of differential equations [4]

$$\frac{\mathrm{d}u_1}{\mathrm{d}t} = -\frac{u_1 - u_2 - U_N - R_2 i(t) + (R_1+R_2)\phi_1}{(R_1+R_2)C_1} \equiv \\ \equiv Q_1 \tag{1}$$

$$\frac{\mathrm{d}u_2}{\mathrm{d}t} = -\frac{u_2 - u_1 + U_N - R_1 i(t) + (R_1+R_2)\phi_2}{(R_1+R_2)C_1} \equiv \\ \equiv Q_2 \tag{2}$$

where ϕ_1, ϕ_2 are defined as

$$\phi_1 = i_1 + \frac{i_2}{\beta_2}, \quad \phi_2 = i_2 + \frac{i_1}{\beta_1} \tag{3}$$

and

$$I_1 = i_{ES1} e^{(u_2/V_T)}, \quad I_2 = i_{ES2} e^{(u_1/V_T)} \tag{4}$$

where β_1, β_2 are the current amplification coefficients, i_{ES1}, i_{ES2} are the saturation currents of bipolar transistors and V_T is thermal voltage. In equations (1),(2) $\equiv$ is the symbol of equivalence and Q_1, Q_2 are constants. If we assume $Q_1 = 0$ then equation (1) has the form:

$$u_1 - u_2 - U_N - R_2 i(t) + (R_1+R_2)\phi_1 = 0\,. \tag{5}$$

By a numerical method it is possible to derive from (5) a transfer characteristic of first inverter $u_1 = f(u_2)$ (see Fig. 3, $Q_1 = 0$).

Table 1. Parameter values of transistors

IS=1.0E−16 A	RC=10 Ω
BF=100	CJC=1 pF
ISC=1.0 E−14 A	CJE=1 pF
RB=100 Ω	VJE=0.75 V
RE=1 Ω	VJC=0.75 V

Table 2. Values of equivalent voltages

$R_2 = 4$ ($k\Omega$)	U_{NE} equation (mV)	U_{NE} SPICE (mA)	I_m (mA)
$R_1 = 5$	50	50.2	0.1
$R_1 = 6$	100	99.3	0.1
$R_1 = 7$	150	151	0.1
$R_1 = 8$	200	201	0.1

3 METHOD OF CONTROL

The design of measurement instruments functioning on the basis of flip-flop sensors is not realistic without an exact analysis of the shape of the control pulse. Their general behaviour is shown in Fig. 2. The control with a fast-rise segment of the control pulse is characterized by the ratio $\frac{I_m}{\delta_1}$ being such that the currents passing through the capacitors are not negligible compared to the transistor currents. In practice the condition is satisfied if $\delta_1, \delta_2 \ll R_1C_1$ and $\delta_1, \delta_2 \ll R_2C_2$ at the same time (theoretically $\delta_1 = \delta_2 = 0$).

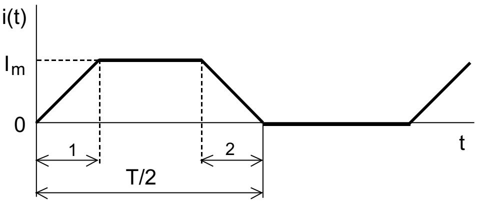


Fig. 2. Current control pulse.

With the parameter values for the circuit, given in Fig. 3, the transfer characteristics of the inverters R_1T_1, R_2T_2 have the shape shown in the same figure.

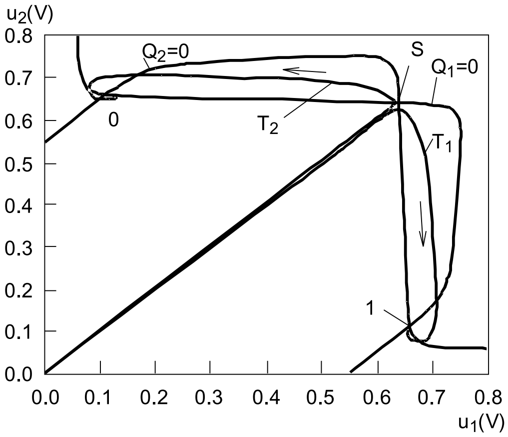


Fig. 3. Transfer characteristic $Q_1 = 0$ and $Q_2 = 0$ corresponding to parameter values $R_1 = 7.3\,\mathrm{k}\Omega$, $R_2 = 7.1\,\mathrm{k}\Omega$, $I_m = 0.1$ mA and $C_1 = C_2 = 1$ pF. The trajectory T_2 corresponds to $U_N = 0$ V, whereas T_1 corresponds to $U_N = 11$ mV.

In Fig. 3 the points $0, 1$ are stable, while the point S is not stable. In Fig. 4 the voltages u_1, u_2 are plotted versus time t.

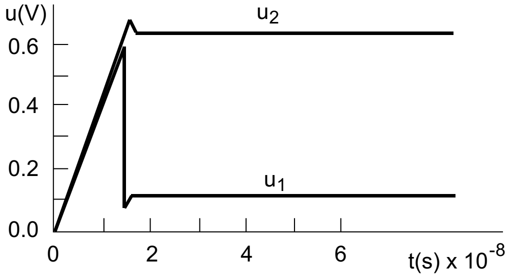


Fig. 4. Voltages u_1, u_2 represent a transition to state 0, for $U_N = 0$, see T_2 in Fig. 3.

4 FORMULA FOR THE EQUIVALENT VOLTAGE

The derivation is based on the fact that in the symmetry state ($U_N = U_{NE}$) the transfer characteristics of the first and second inverter will be symmetrical [2] in such a way that $\frac{\mathrm{d}u_1}{\mathrm{d}t} = \frac{\mathrm{d}u_2}{\mathrm{d}t}$ and $Q_1 = Q_2$. Then the right-hand sides of equations (1), (2) must be equal. Consider mismatches in saturation currents, while other parameters are symmetric. Then $R = R_1 = R_2$, $\beta = \beta_1 = \beta_2$, $C = C_1 = C_2$. From the equal right-hand sides of equations (1), (2) we have:

$$\phi_1 = \phi_2 \tag{6}$$

$$\text{and} \quad U_{NE} = u_1 - u_2 \,. \tag{7}$$

By solving the system (6), (7) we get [2]

$$U_{NE} = V_T \ln \frac{i_{ES1}}{i_{ES2}} \,. \tag{8}$$

The equivalent voltages for the different current gains can be calculated in the same way [2]

$$U_{NE} = V_T \ln \left(\frac{1 - \frac{1}{\beta_1}}{1 - \frac{1}{\beta_2}} \right) . \tag{9}$$

For unequal load resistors of the inverters, from the equal right-hand sides of the equations (1), (2) we have:

$$\phi_1 = \phi_2 \tag{10}$$

$$\text{and} \quad U_{NE} = u_1 - u_2 + (R_1 - R_2) \frac{i(t)}{2} \,. \tag{11}$$

The formula for calculation of the equivalent voltage has in this case form [2]:

$$U_{NE} = (R_1 - R_2) \frac{I_m}{2} \tag{12}$$

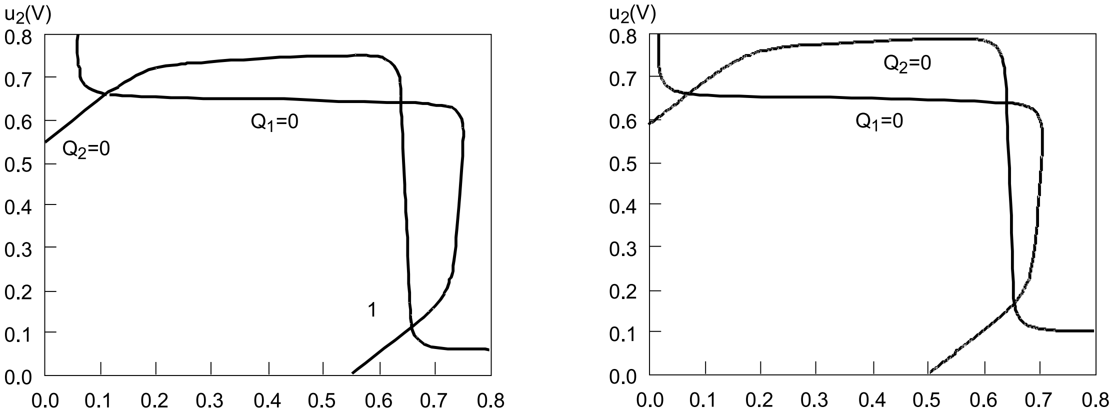
where I_m is the amplitude of the input current impulse (Fig. 2).

Example: in formula (12), for $R_1 = 6\,\mathrm{k}\Omega$, $R_2 = 5\,\mathrm{k}\Omega$ and $I_m = 0.1$ mA, theoretically, according to (12), U_{NE} will be equal to 50 mV and SPICE simulation predicted that U_{NE} is equal to 50.2 mV.

In Fig. 5a are plotted the transfer characteristics of the first and second inverter in a symmetrical state. The transfer characteristics $Q_1 = 0$, $Q_2 = 0$ in an asymmetrical state are depicted in Fig. 5b.

5 EXPERIMENTAL RESULTS

The validity of the formulae for calculation of the equivalent voltage was proved by simulation in SPICE. If the equivalent voltage was too great which resulted in the situation that the simulated flip-flop went to a "one", then, in the next simulation this voltage was given a smaller value, until the flip-flop went to zero. Through



a) b)

Fig. 5 Transfer characteristic $Q_1 = 0$ and $Q_2 = 0$ corresponding to parameter values $R_1 = 6\,\mathrm{k}\Omega$, $R_2 = 5\,\mathrm{k}\Omega, I_m = 0.1$ mA and $C_1 = C_2 = 1$ pF and a) $U_N = 50$ mV, b) $U_N = 0$ V.

such an iteration a small voltage range could by found within which the equivalent voltage resided. The parameter value of the bipolar transistors used are shown in Tab. 1. In Tab. 2 the equivalent voltages are obtained with the aid of the formula and simulation.

In formula (8), for $i_{ES1}/i_{ES2} = 4$, $V_T = 26\,\text{mV}$, U_{NE} will be equal to 35.85 mV according to (8), and SPICE predicted that U_{NE} is equal 35.9 mV. In formula (9), for $\beta_1 = 150$, $\beta_2 = 135$ and $V_T = 26\,\text{mV}$, U_{NE} will be equal to $19.3\,\mu\text{V}$ according to (9), whereas SPICE predicted that U_{NE} is equal $19.7\,\mu\text{V}$. The flip-flop sensor was controlled by a current pulse according to Fig. 2, while $\delta_1, \delta_2 = 10$ ns and $I_m = 0.1$ mA. From the obtained experimental results it follows that the inaccuracy of the equivalent voltage, calculated from relations (8),(9) and (12) is less than 2 %.

6 CONCLUSION

The aim of this paper was to show the properties of the flip-flop sensor controlled by a fast-rise segment of the control pulse. From the formulae derived it is possible to study the effect of flip-flop asymmetry on the equivalent voltage. The asymmetry can be represented by the action of a given non-electrical quantity upon some of the parameters of the flip-flop sensor. The method of measurement by the flip-flop sensor following from the existence of two stable states makes it possible to represent the equivalent voltage or a non-electrical quantity in a digital form without an extra AD converter.

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