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# DEVICE FOR SEMICONDUCTOR CARRIER MOBILITY MEASUREMENT

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**Abstract**

A novel method and a device measuring the mobility of majority carriers in semiconductors using the Hall current is proposed and experimentally tested. The geometry of the mobility-determining structures is similar to the topology of the so-called Corbino disk. The semiconductor wafer, in our case, $n$-silicon, has circular form and two concentric ohmic contacts: one of them in the central zone of the disk, and the other around the circumference. In contrast to this well-known Corbino configuration, the peripheral electrode is interrupted, whereas the size of the so-formed arc is many times smaller than the remaining section of the external perimeter. The two ohmic contacts are brought together to a current source, and the external magnetic field is applied perpendicularly to the disk plane. The ends of the interrupted electrode are connected to an electronic galvanometer measuring the Hall current involved in the Corbino structure. The experiments were carried out at room temperature and in liquid nitrogen. The results obtained with the new device are comparable to the previously known mobility values.

**Key words:** Corbino disk, Hall current, carrier mobility measurement, Lorentz force deflection

**Introduction.** The Hall effect, whose basic concept seems to be an elementary one, features exclusively versatile applications. For example, its use in the measurement of carrier mobility $\mu$ has become an industrial semiconductor characterization standard in micro- and nano-electronics, monolayer graphenes, sensor

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elements, integrated circuits, and others. The discovery of the quantum Hall effect in MOS transistor inversion layers at cryogenic temperatures [1] and the in-plane sensitive Hall phenomenon (vertical Hall elements) [2–5] supplement metrology with a quantum resistance standard and a new generation of high-resolution and high-sensitivity microsensors for the purposes of multidimensional 2D and 3D vector systems. The information signal used in the determination of semiconductor mobility $\mu$ is Hall voltage $V_H$ or Hall current $I_H$ which depend on the applied semiconductor, sensor geometry, magnetic field strength, temperature, biasing conditions and more. The relevant theoretical background and the instrumental solutions are described in [3–12]. However, the experimental implementation of this methodology is complicated by the dependence of the key characteristics $V_H$ and $I_H$ on the direction of the supply current $I_S$ flowing in the semiconductor samples with respect to the crystallographic axes. Furthermore, the results are sensitive to the direction of the magnetic field $\boldsymbol{B}$ with respect to the crystallographic topology. The procedures require labour-intensive preliminary preparation to implement the required structure orientation with respect to the direction of the field $\boldsymbol{B}$ and the current $I_S$ [9]. In so doing, errors arise which may reach up to 30%.

Another method for evaluation of mobility $\mu$ is known, which uses Corbino disk and the magnetoresistance effect, $\mathrm{R}(B) \sim B^2$. It uses a circular semiconductor wafer (ring) made of low conductivity semiconductor and two concentric ohmic contacts: one in the centre and the other electrode on the periphery, connected to a power source [9,13]. Perpendicularly to the ring plane, magnetic field $\boldsymbol{B}$ is applied, whereas mobility is determined by the expression $\mu = (1/B_0)[\alpha(\Delta\,\mathrm{R}(B_0)/\,\mathrm{R}(0)]^{1/2}$ [3,7,9,10]. Despite its simplicity, the disadvantage of this approach is again the reduced accuracy, whereas sometimes the error may exceed 40% on account of: a) the impossibility to determine precisely the magnetoresistance coefficient $\alpha$ whose value is determined by the scattering mechanisms in the material (silicon, germanium, gallium arsenide, indium antimonide, and others) and the dependence of the magnetoresistance on the crystallographic orientation. In this article, a new device and approach for measurement of semiconductor carrier mobility $\mu$ are proposed, which involves Hall current $I_H$ and Corbino disk, whereat the metrological procedure is simplified and the accuracy is increased.

**Samples and experimental methods used.** The geometry of the semiconductor samples used in the new proposal to determine the characteristic $\mu$ of the majority carriers is similar to the geometry of the Corbino disk [3,7,9,10,13], Fig. 1. The semiconductor wafer has circular form and two concentric ohmic contacts 1 and 2: contact 1, located in the central zone of disk, and contact 2, arranged on its periphery.

In contrast to the well-known Corbino topology, in our case, the peripheral contact of length $b$ is interrupted, whereas the size $a$ of the arc is many times smaller than the remaining part of the perimeter $b$, $a \ll b$. The two ohmic electrodes are connected to the supply $\mathrm{E}_S$. The ends M and N of the interrupted

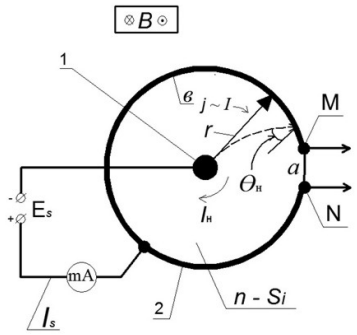



Fig. 1. Corbino disk topology used in Hall current $I_H$ method. The circumference electrode 2 is interrupted by arc a to measure $I_H(I_S, \boldsymbol{B})$

contact 2 are connected to an ammeter, measuring the Hall current $I_H(I_S, \boldsymbol{B})$ involved in the Corbino structure. The internal resistance of this galvanometer is much smaller than the resistance of the semiconductor arc $a$. Perpendicularly to the disk plane, external magnetic field $\boldsymbol{B}$ is applied. The samples are intended for electrical, galvanomagnetic and thermal experiments of purely research nature at the following temperatures: room $T = 300$ K, and a media of liquid nitrogen $T = 77$ K. The chips with the new configuration are assembled on a non-magnetic bronze package of thickness 0.3 mm, which has been previously galvanically gilt with coating of 2–3 µm, thus eliminating the errors from the magnetic hysteresis processes in the standard carriers of type DIL-22. The silicon die is glued onto the lead frame using a two-component, silver epoxide glue, which is then assembled within a body of type DIL-4 and protected by a two-component silicon elastomer intended to remove the possible thermal strains arising during the operation of the Corbino disk chips. The experimental ring-dot samples were prepared specifically and provided to us through the courtesy of Harting Electr. Corp. The experimental prototype was implemented using part of the processing steps generally applied in IC technology. The silicon plate with carrier's concentration in the low-doped $n$-Si substrate is $n_0 \approx 4.3 \times 10^{15}$ cm$^{-3}$ and disk diameter is $d = 560$ µm, Fig. 1. By manufacturer data, the mobility of the majority carriers – electrons, at room temperature $T = 300$ K of the silicon wafers used, as determined by a standard method with Hall voltage $V_H$, $\mu_n \approx 1100$ cm$^2 V^{-1} s^{-1}$.

The investigation at cryogenic temperature $T = 77$ K were made using a glass cryostat (Dewar vessel) in direct liquid nitrogen medium providing the temperature $T = 77$ K (about $-200\,^\circ$C). Its construction is tailored for work in a magnetic field generated by a Weis-type electromagnet with water cooling. At maximal supply power P = 1.2 kW and distance between the pole concentrators, $l = 20$ mm, induction $B = 2.2$ T is reached. The electromagnet is power-supplied by a stabilized current source of type HP 6010A DC. The calibration of the magnetic field $\boldsymbol{B}$ is permanently controlled by a standard 3D magnetometer of type Metrolab – THM 7025 manufactured by Schaefer Corp. With galvanomagnetic experiments,

high homogeneity rate of the field $\boldsymbol{B}$ is provided, since the individual area of the magnetic poles is 25 cm$^2$, and the distance between them is $l = 2.0$ cm. The error at measurement of induction $B$ is equal to the sum of the individual errors of the sensor registering the field $\boldsymbol{B}$ and the signal processing electronics. In practice, each of these errors is about $\approx \pm 0.5\%$. From here, it follows that the total error at determination of field $\boldsymbol{B}$ does not exceed $\sim \pm 1.0\%$. The specific operating method at temperature $T = 77$ K is the following: ) The sample with Corbino structure is placed in the socket of a dedicated non-magnetic holder and is fixed into the Dewar vessel (cryostat); *b*) The liquid nitrogen is gradually poured in through the cryostat's input opening. The zone with the studied Corbino configurations should be poured over in no less than 35–45 min; otherwise, as a result of the enormous temperature gradient, the semiconductor samples will be broken or irreversible negative changes in the elements' characteristics will occur, which will render the study useless; *c*) At reaching temperature $T = 77$ K, the device's supply is activated and the measurements are conducted. The experimental temperature $T$ is determined by a diode working in current mode of operation, $I = \text{const}$. In this case, the voltage $V_{EB}(T)$ is linear function of the parameter $T$ with coefficient TC $\approx -2$ mV/ °C [3, 14]. The error at the temperature studies is typical for this experimental method and it is $\pm(0.5 \div 1.0\,^{\circ}\text{C})$.

The measurements of the electric and galvanomagnetic parameters were conducted in the dark conditions using semiconductor structure analyser Keithley 4200A-SCS. The results obtained at fixed value of the supply current $I_S = \text{const}$ for both directions of the magnetic field $\pm\,\boldsymbol{B}$ were averaged. In some experiments, the Hall current $I_H$ was measured by the electronic galvanometer Tektronix.

**The Corbino current $\boldsymbol{I_H}$ method.** The new device, Fig. 1, functions as follows. Upon applying the voltage $V_S$ between the central electrode 1 and the peripheral contact 2, the respective electric field features radial geometry, whereas the equipotential lines are concentric. In the absence of external magnetic field $\boldsymbol{B}$, the current $I_S$ in the Corbino disk is radially directed. The application of field $\boldsymbol{B}$ vertically to the structure's plane is manifested by Lorentz force, $\boldsymbol{F}_L = q\boldsymbol{V}_{dr} \times \boldsymbol{B}$, tilting the vector of the density of the supply current $j \sim I$ with respect to the disk's geometric radius $r$ at averaged Hall angle, $\operatorname{tg}\theta \approx \mu B$, where $q$ is the elementary electron charge [3, 7]. This is why the integral effect of the magnetic field $\boldsymbol{B}$ in the Corbino structure is a lateral deflection of the carriers only by the force$\boldsymbol{F}_L$ at angle $\theta \sim \mu B$. In this, the azimuthal shift of the $I_S$ current lines in the disk, depending on the direction of the field $\boldsymbol{B}$ and the current $I_S$, is clockwise or anti-clockwise. Therefore, there is no Hall field, $\boldsymbol{E}_H$, $\boldsymbol{F}_L \approx \boldsymbol{E}_H$, balancing the Lorentz force $\boldsymbol{F}_L$, on account of the "endless" circular geometry of the sample and the absence of isolating boundaries where charge could accumulate, i.e. the field $\boldsymbol{E}_H \approx 0$ [3, 4, 7, 9]. The essential peculiarity of the action of the structure from Fig. 1 is that Hall current $I_H(I_S, \boldsymbol{B})$ is generated by Lorentz force $\boldsymbol{F}_L$ and no component of the short-circuited effect of Hall voltage $V_H$ is sure to

arise. Therefore, in Corbino structures, quadratic geometric magnetoresistance develops, MR $\sim B^2$, [3,7,9]. It may be experimentally registered by measuring the field between the central contact 1 and the peripheral one 2. However, for the purposes of the new method, the signal $V_{MR} \sim B^2$ is a parasitic one and it is compensated by the disk's construction. This lateral deviation of the current $I_S$ in the Corbino structure caused by magnetic field $\boldsymbol{B}$, respectively Lorentz force $\boldsymbol{F}_L$, generates circulating current which is essentially Hall current, $I_H$. In this type of samples with different area of the supply contacts 1 and 2, the distribution of the electric field is not homogenous, whereas the carriers' drift velocity $V_{dr}$, as well as Lorentz force $\boldsymbol{F}_L \quad \sim V_{dr}$ reduces from centre to periphery. The transversal Hall current $I_H(I_S, \boldsymbol{B})$ flowing in the disk generates simultaneously circulating current in the peripheral contact $b$ itself by the electromotive force $\boldsymbol{F}_L$. This is the key physical prerequisite of the new metrological technique, motivating the need of the arc $a$. Thus, the azimuthal (transversal to the radius $r$ of the structure from Fig. 1) Hall current $I_H(I_S, \boldsymbol{B})$ is determined by the expression $\pm I_H(I_S, B) \approx \pm A(a/b)\mu B I_S$, the sign being (+) when the carriers are holes, and (−) when they are electrons [3,7,9,10]. The coefficient $A$ is a geometrical correction factor in the Hall current technique. It is related with the electric field generated in the sample by the supply current $I_S$ and the part of the current $I_H$ flowing through the peripheral contact 2. Its value is determined empirically and it is a function of the Corbino disk's geometrical parameters and the strength of the supply $I_S$. The current $I_H$ is determined by the averaged bulk mobility $\mu$ of carriers in the semiconductor. Therefore, by measuring the signal $I_H$ and using the expression for the mobility $\mu_n \approx A(bI_H)/(aB_0I_{S_0})$, at fixed current $I_{S_0} = \text{const}$ and induction $B_0$, the parameter $\mu_n$ of the majority carriers in the semiconductor material, such as electrons, is evaluated.

**Circuitry and measurement.** The innovative task in the solution from Fig. 1 is to take away the Hall current $I_H(I, \boldsymbol{B})$ flowing in the peripheral contact

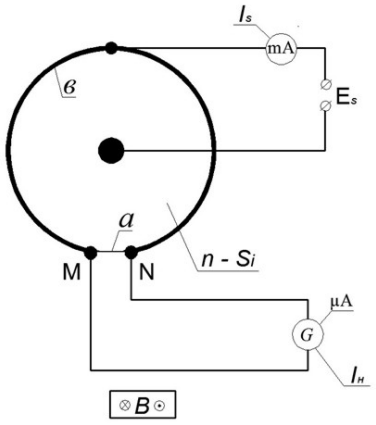



Fig. 2. Circuitry containing $n$-Si Corbino disc for Hall current $I_H(I_S, \boldsymbol{B})$ measurement

for measurement. This is achieved by the arc adjoined to the ends M and N of the ammeter circuit of arcs  or $b$, i.e. electronic galvanometer G with high sensitivity, Fig. 2, determining the information signal $I_H$ [9,10].

In the absence of field $\boldsymbol{B}$, the supply current $I_S$ from the source $E_S$ flows through contacts 1 and 2 of the structure. The circuitry is simplified, compared to the scheme containing variable resistors [3,7,9,10]. At field $B = 0$, the Hall current $I_H$ is zero, $I_H(I, B = 0) = 0$, whereas the electronic galvanometer G registers no current $I_H$. An important peculiarity of the Corbino samples with the new method is the value of the resistance $R_a$ of the semiconductor arc $a$ interrupting the peripheral ohmic contact $b$. A key factor here is that the internal resistance $R_G$ of the galvanometer G should be of an order smaller than the resistance of the arc $R_a$, $R_a \gg R_G$. Under these conditions, the Hall current $I_H(I_S, \boldsymbol{B})$ in the magnetic field $\boldsymbol{B} \neq 0$ will pass through the instrument G to be measured. The characteristics in the expression for the mobility $\mu_n$: the Hall current $I_H$, the geometrical sizes  and $b$, the magnetic induction $B_0$ and the supply current $I_S$ are subject to registration with increased instrumental accuracy and the simple but effective setup from Fig. 2. The new solution provides information for another important characteristic of the majority semiconductor carriers. Depending on the direction of the current, $-I_H$ or $+I_H$, at previously fixed polarity of the magnetic field $\pm\boldsymbol{B}$ and the supply $\pm I_S$, the sign of the current carriers, electrons $(-)$ or holes $(+)$, is determined [15]. This is an advantage of the configuration from Fig. 2.

In contrast to the already known settings with complicated experimental procedure, the new device, Fig. 1 and Fig. 2, is based on a clear, well argumented and simplified metrological principle providing for precise and express operation. The novel Corbino method features the following advantages: 1. High metrological accuracy, since the mobility $\mu$ is not determined by the magnetoresistance and a number of ad hoc assumptions and approximations are lacking, and the parameters in the expression for the mobility $\mu$ are registered by widely accepted high-precision metrological instruments; and 2. Simplified experimental setup because of the avoided need of the respective orientations of the semiconductor's crystallographic axes with respect to the current $I_S$ and the magnetic field $\boldsymbol{B}$.

**Results.** The behaviour of the Hall current $I_H(I, \boldsymbol{B})$ as a function of the magnetic induction $B$ is shown in Fig. 3 and Fig. 4. The field $B$ is relatively low and constitutes no more than $B \leq 0.7$ T at temperature $T = 300$ K and $B \leq 0.4$ T at $T = 77$ K. These values are appropriate to bring to a minimum the negative effects of the quadratic magnetoresistance component MR $\sim (\mu B)^2$ in the mobility $\mu_n$ of field $\boldsymbol{B}$ [16].

The experiments were carried out for three values of the supply current $I_S$. The obtained plots of the Hall current $I_H(I, \boldsymbol{B})$ with the magnetic field $\boldsymbol{B}$ are linear. The non-linearity of the dependences is no more than 0.6%. The variation of the Hall current with the magnetic field proves that, in the peripheral contact 2

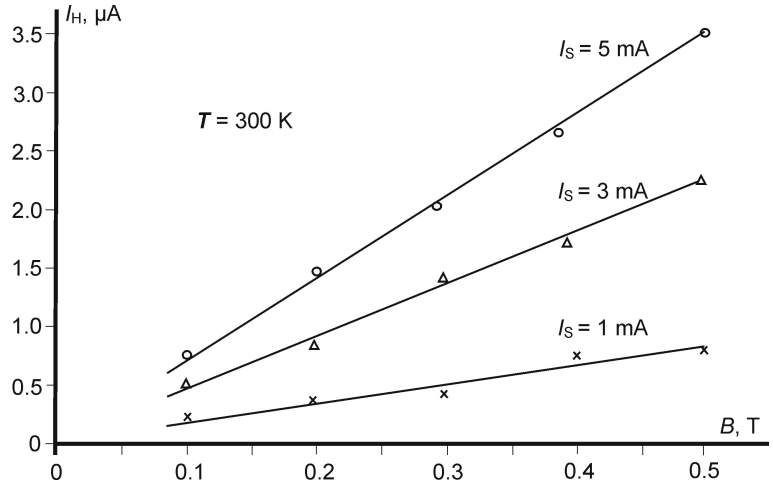



Fig. 3. The Hall current $I_H(I_S, \boldsymbol{B})$ as a function of the magnetic induction $B$ at room temperature $T = 300$ K, the supply current IS is a parameter

of the Corbino disk in orthogonal magnetic field $\boldsymbol{B}$, a linear Hall signal $I_H(I, \boldsymbol{B}) \sim \boldsymbol{B}$ circulates. According to the method and the device in [15], the mobility $\mu_n$ of the electrons in the prototype samples constitutes about $\mu_n \approx 1015$ cm$^2$V$^{-1}$s$^{-1}$ at temperature $T = 300$ K and $\mu_n \approx 5030$ cm$^2$V$^{-1}$s$^{-1}$ at $T = 77$ K.

Comparing the obtained values for the mobility at $T = 300$ K with the value provided by the manufacturer for the samples and from the detailed studies in [17] for $\mu_n$ ($\mu_n \sim 5100$ at $T = 77$ K and donor concentration $10^{15} < n_0 < 10^{16}$), it can be seen that the results are comparable. At room temperature and magnetic fields $B > 0.7$ T, and at $T = 77$ K and $B > 0.4$ T, in the plots from Fig. 3 and Fig. 4, non-linearity arises, whereas with higher values of the current $I_S$, it is more clearly manifested.

The most probable reason therefore is the quadratic geometric magnetoresistance, MR $\sim B^2$ involved. Apart from this, with preliminary known directions of the current $\pm I_S$ and the magnetic field $\pm\boldsymbol{B}$, from the sign of the Hall current in our experiments, it was established that the majority carriers in the samples are electrons, i.e. the semiconductor is $n$-Si.

**Conclusion.** The novel Hall current technique using non-standard configuration of the Corbino disk (interrupted peripheral ohmic contact) and taking out of the characteristic $I_H$ for measurement is well-suited for semiconductor technology. The method provides information both for the mobility $\mu$ of the majority carriers, as well as for their sign. Moreover, the experimental setup is simplified and features enhanced accuracy. The parameters included in the expression for Hall current are measured by high-class digital instruments. The functioning of the new device allows for high temperature range – from room to cryogenic tem-

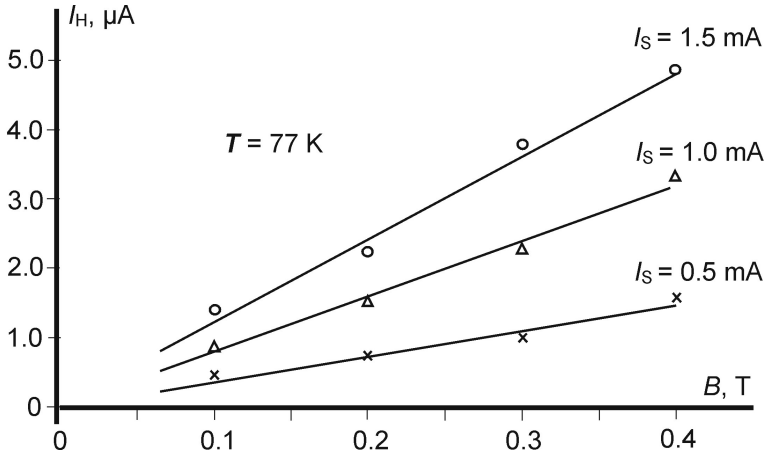



Fig. 4. Plots of the Hall current at liquid nitrogen temperature $T = 77$ K, the supply $I_S$ is a parameter

peratures, which makes it a convenient instrument in micro- and nano-electronics, sensorics, integrated circuits and more. The new measurement procedure is also appropriate for semiconductors, such as GaAs, InSb, InP, and others, whereas it provides very useful information about the transport process of carriers and the scattering mechanisms of charges involved.

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## REFERENCES

[1] Klitzing K. von, G. Dorda, M. Pepper (1980) New method for high-accuracy determination of the fine-structure constant based on quantized Hall resistance, Phys. Rev. Lett., **45**(6), 494–497.
[2] Roumenin Ch., P. Kostov (1983) Planar Hall sensor, BG Patent No. 37208 B1/26.12. 1983.
[3] Roumenin C. (1994) Solid State Magnetic Sensors, Amsterdam, Elsevier.
[4] Roumenin C. (2006) Microsensors for magnetic field. In: (J. G. Korvink, O. Paul, eds), MEMS – a practical guide to design, analysis and application, W. Andrew Publ., USA, 453–521.
[5] Lozanova S. V. (2009) Parallel-field silicon Hall effect microsensors with minimal design complexity, IEEE Sensors Journ., **9**(7), 761–766.
[6] Ramsden E. (2006) Hall effect sensors – Theory and application, 2nd ed., Elsevier, the Netherlands.
[7] Popovic R. (2004) Hall effect devices, 2nd ed., The Adam Hilger series on sensors, Bristol, IOP Publ. Ltd.
[8] Seeger K. (1989) Semiconductor Physics, Springer.

[9] Vorobiov U. V., V. N. Dobrovolskii, V. I. Striha (1988) Semiconductor research methods, Kiyv, V. Skola (in Russian).
[10] Pavlov L. P. (1975) Methods of determining the main parameters of semiconductor materials, Moscow, V. Skola, (in Russian).
[11] Sze S. M. (2007) Physics of Semiconductors, 3rd ed., John Wiley & Sons – Intersc. Publ., New York.
[12] Ripka P. (2001) Magnetic Sensors and Magnetometers, London, Artech House Books.
[13] Corbino O. M. (1911) Elektromagnetische Effekte, die von der Verzerrung herrühren, welche ein Feld an der Bahn der Ionen in Metallen hervorbringt, Phys. Z., **12**, 561.
[14] Lozanova S. V., S. A. Noykov, A. J. Ivanov, C. S. Roumenin (2015) Functional multisensor for temperature and subsequent 3D magnetic-field measurement, Proc. Engin., **120** 824–827.
[15] Lozanova S. V., M. L. Ralchev, C. S. Roumenin (2021) Device for carrier mobility measurement in semiconductors, Patent Appl. BG No. 113439 A/27 Octob.
[16] Bate R. T., A. C. Beer (1961) Influence of conductivity on galvanomagnetic effects in semiconductors, J. Appl. Phys., **32**(5), 806—814.
[17] Morin F. J., J. P. Maita (1954) Electrical properties of silicon containing arsenic and boron, Phys. Rev., **96**(1), 28–35.

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